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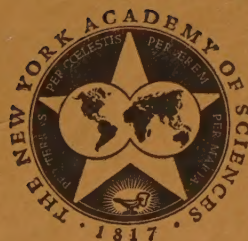
**CONTRIBUTIONS OF THE PHYSICAL, BIOLOGICAL,
AND PSYCHOLOGICAL SCIENCES IN HUMAN DISABILITY**

BY

RENATO CONTINI AND SIDNEY FISHMAN (*Conference Co-Chairmen*), I. J. BRIGHTMAN, D. H. DABELSTEIN, R. DRILLIS, W. E. FRANK, W. B. HABER, G. G. HIRSCHBERG, H. A. IMUS, K. S. LANDAUER, D. R. LINDSAY, B. D. LITT, M. MARKS, H. A. MAUCH, L. MEYERSON, M. A. SEIDENFELD, W. A. SPENCER, A. STAROS, S. A. WEISS, AND H. K. WORK

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RENATO CONTINI



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INTRODUCTORY REMARKS

By Renato Contini

College of Engineering, New York University, New York, N. Y.

Every branch of science is expanding as more discoveries are made and as new tools, instruments, and techniques make still more discoveries possible. In any field, the individual scientist finds himself in the predicament of requiring greater knowledge in his specific area, even as this area becomes a smaller and smaller portion of the total spectrum of science.

The problems that present themselves for solution tend increasingly to call upon a broad range of scientific skills. This indicates, therefore, a need for an interdisciplinary approach and suggests a growing demand for interdisciplinary research. Many instances of this growing tendency might be drawn at this time from many fields of activity. The area that perhaps most demands concerted cross-disciplinary action is that which deals with man, particularly when he is physically disabled.

It is normally accepted that the medical and biological scientists are concerned with the physically handicapped or disabled. It is generally appreciated that a person who has suffered physical trauma may also suffer emotionally from his affliction, and that the psychological scientist is also concerned with his rehabilitation. What has not been considered until very recently is that the physical or engineering scientist can contribute significantly to a better understanding of the physical disability and, hence, to the physical means leading to rehabilitation.

The physical scientist can make his contributions in three major ways.

First, he can contribute to a better understanding of the physical phenomena of human performance. He can accomplish this by applying the laws of mechanics to human movement and by applying structural principles to the skeletal-muscular complex.

Second, he can contribute to the development of improved instrumentation for the diagnosis of the ailment and for the measurement of its extent. New and improved electronic and optical devices have made it possible to examine the skeletal structure in motion, to measure muscular activity and energy costs, and to measure muscular effort against minutely discrete time scales.

Third, he can contribute to the development of prostheses and other devices to replace or substitute for lost functions. Hearing and visual aids are physical devices that have been improved by the application of recent technological knowledge. Artificial arms and legs and other assistive devices and new methods for supplying power are newer contributions from the engineer.

A most striking demonstration of cooperation among biological, psychological, and engineering sciences has been in the field of prosthetics. For more than ten years, under government auspices, scientists from these fields have worked with lower- and upper-extremity amputees, and have studied their patterns of activity, their emotional attitudes, and their medical adapta-

tion to different prostheses. In this area, they have made significant contributions to provide the amputee with more adequate function and a happier outlook.

Many cooperative ventures have been conducted in the areas of neuromuscular and sensory disabilities, perhaps not as extensively in the past as is the case today, but with equal scientific interest.

The New York Academy of Sciences, believing that it was appropriate at this time to review in part what has been done in these three areas of disabilities and to consider what progress is being achieved in cooperative interdisciplinary research, sponsored the conference on which this publication is based. The Academy and the organizers of this program were particularly gratified to find that so many scientists and research administrators were willing to participate in the program.

Part I. Amputation

THE APPLICATION OF ENGINEERING TECHNOLOGY TO THE SIMULATION OF HUMAN MOTIONS

By Hans A. Mauch

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The application of engineering technology to the problem of simulation of human motions lost due to amputation covers such a wide area that, within the limitations of this paper, it will be possible only to discuss it in general terms. For better illustration, however, I shall include, as a second part, the detailed discussion of a typical example.

Part I

In approaching a problem of simulation it appears logical first to describe the mechanism to be simulated. In doing this it will be helpful to use engineering terms, since the simulation is to be carried out by the application of engineering technology.

The mechanism involved in producing human motions includes bones, joints, muscles, and nerves. In describing the properties of these biological elements we shall discuss also the properties of their possible technological substitutes. This will allow us to assess the feasibility of simulation as far as the elements are concerned.

As a structural material, the human bone has a tensile strength of the order of 20,000 psi, a compression strength of the order of 25,000 psi, an elasticity modulus of close to 3×10^6 psi, and a specific gravity of about 1.9.¹ Although these values could be matched fairly well in artificial limbs by several materials, for instance, magnesium alloys, actually a wide variety of materials is being used, with properties differing substantially from those of bones. This indicates that close matching of properties, although possible, is considered unimportant in this case.

Essentially, human joints are bearings. While little can be found in the literature about their mechanical characteristics, some simple calculations show that the maximum loads occurring in joints are of the order of a few hundred psi, and that the relative speed between the joint surfaces does not exceed a few inches per second. By comparison, technical bearings, such as the self-lubricating powdered metal type, have load ratings of several thousand psi at these speeds, and up to 30,000 psi static load capacity, which is more than bones could support.

The simulation of some body joints presents certain kinematic problems. The best known case is the knee joint. In the so-called polycentric knee joints these problems have been solved. However, there is some doubt that complete simulation in this respect is essential.

The skeletal muscle has a triple function. In lengthening under load it absorbs mechanical energy and serves as a damping device; in shortening

under load it performs mechanical work and serves as an actuator; in supporting static load it neither receives nor supplies mechanical energy, but serves as a lock. Typical forces per unit area of muscle cross section during such activities are of the order of 50 psi,² and contraction velocities during the actuator function may reach values up to 5 feet per second.³ Although it is relatively simple to duplicate these characteristics by technical damping devices, actuators, and locks, we must take into consideration, in the case of technical actuators, the fact that they receive their energy in the convenient form of a high pressure fluid, or as electrical energy, while a muscle uses chemical fuel and must convert it into mechanical energy. Much to the regret of mechanical engineers, it is not fully known how the muscle does this with the impressive efficiency of 40 per cent⁴ and without obvious effort. What has become known, due to the efforts of physiologists and biochemists over the past decades, adds up to a most fascinating research report. Unfortunately, for the time being, we must simulate muscles with conventional actuators which, although feasible, is not a particularly elegant solution. Generally speaking, there is a greater need for actuators in upper extremity prosthesis; in lower extremity prosthesis, damping devices have the wider field of application. Locks are used in both upper and lower extremity prostheses.

The role played by the nerves in the motion of human limbs is twofold. They transmit motor signals from the central nervous system to the muscles, and they feed back information on limb position and pressure sensations to the central nervous system. Their signal transmission velocity of several hundred feet per second,⁵ not counting the synaptic delay, is quite slow as compared with the signal transmission velocities in an electronic control system. There is some superiority on the part of nerves with respect to space requirements, both for the nerve fiber itself and for the pressure and kinesthetic receptors. However, the space needed for their technical counterparts would in no way be prohibitive. The fact that these counterparts hardly have been employed thus far in artificial limbs, as we shall see, is explainable by other reasons.

It appears then that we could duplicate the biological elements by the technological elements without much compromise. If we now move on from the element level to the system level and investigate again the feasibility of simulation, we arrive at a similar result: we could join any number of artificial bones by bearings, thus duplicating the skeleton of a limb; we could install actuators, damping devices, and locks in the right places, thus duplicating the muscles; we could control them electronically, thus duplicating the motor nerves; and we could produce signals indicating positions and pressures throughout the system, thus duplicating the sensory nerves. In other words, we could build a fairly good functional replica of a limb lost due to amputation.

Why, then, do we not build this near-perfect prosthesis? Or, more specifically, why do we limit the motion of artificial thumbs to a few fixed positions instead of providing them with continuous motion? Why do we

design certain arm prostheses in such a way that the amputee must carry out motions in sequence rather than simultaneously? Why do we encourage the amputee to keep his eye on the arm prosthesis during difficult activities? Why do we, in above-knee prosthesis, support the amputee's weight by making him sit on the upper rim of the socket rather than using whatever is left of the femur for this purpose? Why do we actuate knee locks by gravity and acceleration forces or by heel contact? Why do we control the swing of above-knee prostheses by damping devices with a built-in damping program? The answer obviously is that the near-perfect prosthesis would be of doubtful value, because we should not know how to enable the amputee to operate it. In other words, we are confronted here with the central problem of human-factors engineering, the problem of how to integrate, in a man-machine combination, the machine and the man or, in our case, how to break through the barrier separating the prosthesis and the amputee.

This fact may call for a reorientation of our thinking. To put it somewhat paradoxically: the main loss in an amputation is not so much the loss of a limb, because this we could replace by a fairly good duplication of the original, but consists in the drastic reduction of the number and quality of information channels available for communication with the artificial limb, and of the number and quality of mechanical links for the transmission of skeletal and muscle forces to and from it. This problem of transmission of information and forces between amputee and prosthesis represents the crucial difficulty in simulating human motions in artificial limbs.

We overcome this difficulty by a wide variety of sometimes very ingenious compromises. We use prepositioning of limb elements such as thumbs and elbows where continuous motion seems less important. We lump motions of several elements, such as index and middle finger, into one combined motion which then can be carried out by one remaining muscle. We make it possible for motions that need not be simultaneous, such as elbow bending and finger closing, to be carried out in sequence, using the same muscle for more than one motion. We encourage visual feedback as a substitute for kinesthetic feedback. We tunnelize muscles of the stump and its surroundings in order to obtain additional voluntarily controlled motions. We provide suction sockets and end-bearing sockets for better transmission of forces and motions between stump and prosthesis. In lower extremity prostheses, where a predominant pattern of motions is repeated fairly regularly, we produce automatic control actions by using causal relationships within the pattern, for example the fact that locking of the knee becomes desirable, if the heel strikes the ground or the shank reaches a certain position in space. We use also sequential relationships within the pattern for producing program control, for instance, by providing a certain damping profile during the swing phase, as we shall see in more detail in Part II of this monograph.

This list could be extended considerably. It is a list of compromises that, for all practical purposes, are achievements. They represent substantial benefits for the amputee and, therefore, progress. However, the persistent

thought remains, how could we make possible the use of a more perfect prosthesis? Or, in other words, how could we open up more communication channels to give the amputee better control of the prosthesis, and how could we provide improved transmission of forces between them? This last question leads to what has been called skeletal attachment of the prosthesis which, in turn, would allow better use of muscle tunnelization, particularly in lower extremities. The first question suggests some kind of electric tapping of the nerve ends left in the stump as a result of the amputation. Both suggestions present problems of extraordinary difficulty, but perhaps we should consider this a challenge rather than a deterrent.

Part II

Let us now turn to a practical example: the simulation, in an above-knee prosthesis, of the swing-phase motions of the human leg. These motions represent, of course, only a small part of the functions of the muscles involved (quadriceps and hamstring groups). The simulation of other functions of these muscles as they occur, for instance, in walking downstairs or upstairs, is a much more complicated problem. Nevertheless, it has required over four years of intensive work to develop our so-called hydraulic swing control system from the basic concept to the production model now entering field tests. It may be interesting to note that, throughout this time, the basic concept has never been changed; most of the work was caused by what is usually referred to as "minor engineering difficulties" such as overstress, wear, or noises. This experience seems to be quite typical for this branch of human-factors engineering. The problem of simulating the swing-phase motion of the human leg can be visualized best by observing an above-knee amputee walking on a conventional prosthesis at various stepping frequencies called "cadences." Since such a prosthesis has a practically free knee, the lower leg acts essentially like a pendulum. The natural frequency of this pendulum dictates the cadence. If the amputee tries to increase the cadence by moving his stump forward more vigorously, he succeeds only in making the heel of the prosthesis swing higher, and still must wait through the time period set by the natural frequency of the lower leg pendulum until the prosthesis has reached its fully extended forward position, which allows him to put it on the ground and to transfer his weight onto it without risk of buckling of the knee joint. Thus the only way for him to increase his walking speed is to take longer steps.

A normal person, by comparison, can walk faster by increasing his cadence. In doing this he changes the pattern of his leg motions very little. This pattern, at the faster cadence, looks quite similar to a film of his normal gait run with a somewhat higher speed. Since the maintenance of this pattern, independent of the cadence, is, of course, the result of suitable changes of the muscle forces acting on the leg joints, the question, in the particular case of the above-knee prosthesis, is this: What changes of the forces acting on the knee joint during the swing phase are necessary if we are to maintain the pattern of the lower leg motions independent of the cadence?

Let us investigate this question in a more general way. Suppose a mass

particle moves arbitrarily but periodically in a coordinate system, and y denotes the instantaneous position of this particle, as measured along one coordinate of the system. This motion can be expressed by the Fourier series given in the equation

$$y = C_0 + \sum_{n=1}^{n=\infty} C_n \cos (n\omega t + \varphi_n) \quad (1)$$

In the equations

$$y' = - \sum_{n=1}^{n=\infty} n\omega C_n \sin (n\omega t + \varphi_n) \quad (2)$$

and

$$y'' = - \sum_{n=1}^{n=\infty} (n\omega)^2 C_n \cos (n\omega t + \varphi_n) \quad (3)$$

first and second derivatives of EQUATION 1, respectively, y' represents the velocity and y'' the acceleration or deceleration of this moving mass particle. Since mass $\times$ acceleration = force, and since we may consider our particle to have unit mass, EQUATION 3 is also a measure of the forces necessary to make the mass particle move the way it does.

If we consider the lower leg of an above-knee prosthesis to be composed of such mass particles, the motion of each of these around the knee joint can be expressed by the same type of equation as EQUATION 1. The corresponding EQUATION (3) multiplied with the distance of an individual unit mass particle from the knee joint, gives the torque about the knee joint necessary to make that mass particle move the way it does. The sum of the torques of all the individual mass particles comprising the lower leg represents the total torque about the knee joint necessary to move the lower leg the way it does. The individual torque equations comprising this sum have the factor $(n\omega)^2$ in common, because the mass particles comprising the lower leg are locked together, resulting in common motions differing only in amplitude, which varies linearly with the distance of each particle from the knee joint. The fact that the expression $(n\omega)^2$ is governing the torque about the knee joint necessary to make the lower leg move the way it does, permits the general statement that this torque, as far as it is determined by internal inertia forces, must vary with the square of the cadence as expressed by ω , if the motion pattern of the prosthesis is to be maintained in spite of cadence variations. This assumes, of course, that no external force such as gravity is acting upon the lower leg. We shall return to this assumption later.

Before we turn to the question as to what possible physical mechanisms may provide us with forces that vary with the square of the cadence, we must learn something about the direction of these forces with respect to the direction of the related motions. The importance of this point becomes evident if we remember that, whenever force and motion have the same direction, we must supply energy while, whenever they are opposed to each other, we must provide merely for energy dissipation, which is a much simpler problem.

Fortunately, we know from measurements carried out at the University of California⁶ that throughout the swing phase of the natural leg the power requirements at the knee joint are zero or negative. This means that what we need is a damping mechanism that produces frictional forces that vary with the square of the cadence. A close approximation of this desired function can be achieved with a dashpotlike device in which a fluid passes through a restriction under conditions characterized by a Reynolds number well within the range of turbulent flow ($R_n > 3000$ to 4000).

However, this finding represents only a partial solution of our problem. To learn why, we return to EQUATIONS 2 and 3 and take into consideration the fact that the swing of the lower leg remains essentially a pendulumlike motion, even if we force it into a certain pattern and make it independent of cadence variations. This means that the fundamental frequency obtained by making $n = 1$ in both equations is dominant, and that the higher harmonics effect only limited modifications of the basic sine and cosine shape of the fundamental curves. This sine-cosine relationship between EQUATIONS 2 and 3 indicates a 90° phase shift between the maximum forces as expressed by EQUATION 3 and the maximum speed as expressed by EQUATION 2. In other words, the maximum forces occur at the front and rear end of the swing, where the speed becomes zero, and the minimum forces occur in the middle of the swing, where the speed reaches a maximum. Unfortunately, a dashpotlike device develops its maximum forces in phase with its maximum speeds, which means, in our present case, that we would have maximum friction where we need it least and minimum friction where we need it most. However, this is true only if we think in terms of a device that has a fixed restriction for fluid passage. By simply varying either the cross-sectional area of the restriction or the number of fixed restrictions as a function of the position and stroke direction of the device, we can provide a wide variety of phase relationships and damping profiles, including the one most closely approximating the muscle forces in the natural leg.

Let us now proceed to the practical realization of the basic concepts discussed so far. In FIGURE 1, the drawing on the right shows an above-knee prosthesis consisting of thigh (1), shank (2), foot (3), and knee joint (4), equipped with the hydraulic swing control system (5) connected with the thigh by a bolt (6) and with the shank by a bolt (7). This arrangement produces compression of the hydraulic system whenever the leg is bent, and expansion whenever the leg is extended.

The drawing on the left shows the hydraulic system proper, comprising piston rod (8), piston (9), which is mainly a guiding means within the cylinder (10), and hydraulic fluid (11).

A second smaller piston (12) moves up and down within the control bushing (13), which is tapered at the upper and lower end and is screwed into the housing (14), the bottom of which forms an inside taper enclosing the lower tapered end of the control bushing (13). The conical gap between these two tapers can be widened or narrowed by screwing the control bushing (13) up or down within the housing (14). Also screwed into the housing (14) is the cover screw (15), which has an inside taper facing downward and enclosing

the upper tapered end of the control bushing (13). The conical gap between these two tapers can be widened or narrowed by screwing the cover screw (15) up or down within the housing (14).

A number of channels (16) originate from staggered holes in the lower inside wall of the control bushing (13) and terminate within the upper conical

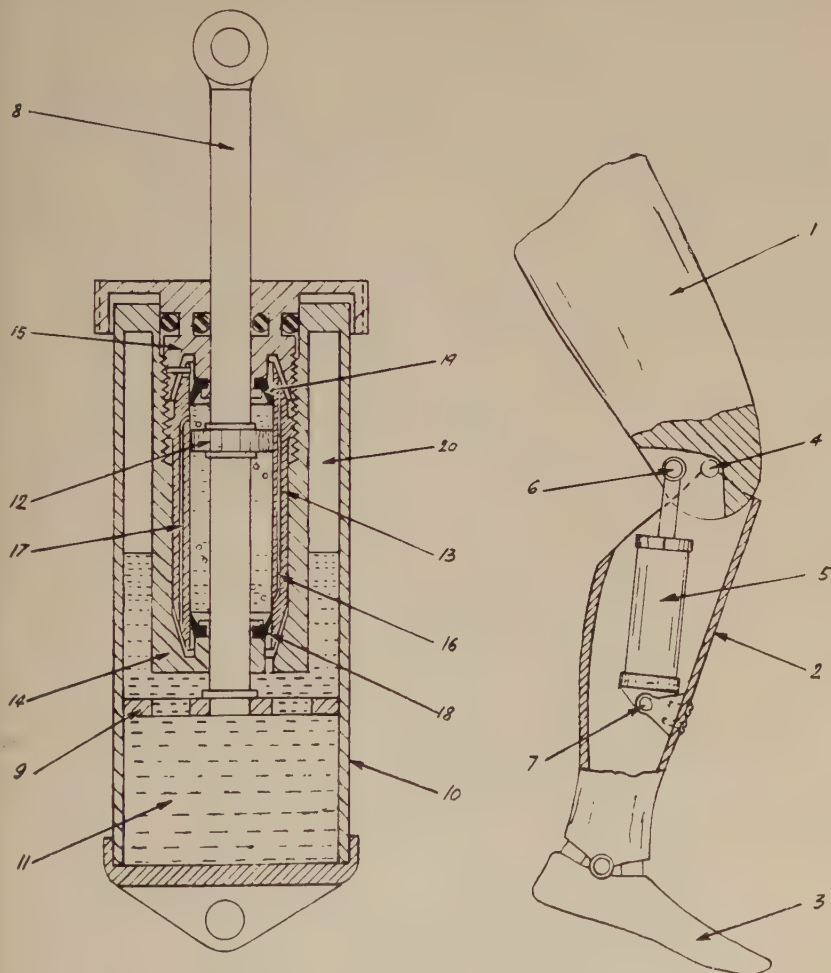


FIGURE 1. Hydraulic swing control system.

gap. Another set of channels (17) originates from staggered holes in the upper inside wall of the control bushing (13) and terminates within the lower conical gap. Lip seals (18 and 19) prevent escape of fluid from the lower and upper ends of the control bushing (13), respectively, but permit fluid entrance into the bushing, thus acting as check valves. Air space (20) allows the fluid level to rise whenever the piston rod (8) is pushed into the system.

At the beginning of the swing phase the prosthesis is bent, the hydraulic system (5) is compressed, and the small piston (12) moves downward within the control bushing (13). The fluid pressure below the piston (12) keeps the lip seal (18) closed, and the fluid flows through the staggered holes in the lower inside wall of the control bushing (13) into the channels (16), then up to the upper conical gap, and from there through the lip seal (19) into the space above the piston (12), thus closing the fluid cycle. While, at the beginning of the compression stroke, all the channels (16) serve as fluid passages, their number decreases, as the piston (12) passes over more and more of the staggered holes in the lower inside wall of the control bushing (13). The progressive flow restriction thus produced depends, regarding the damping profile, on the arrangement of the staggered holes and, regarding the damping degree, on the width of the upper conical gap, which can be adjusted from the outside to satisfy individual need. Basically the same events occur during the expansion stroke, except that the functions of the lip seal (18), of the lower staggered holes, of the channels (16), and of the upper conical gap are now taken over by the lip seal (19), the upper staggered holes, the channels (17), and the lower conical gap, respectively.

The arrangement of the upper and lower staggered holes need not be the same. Actually, the holes are arranged in such a way that optimal simulation of the muscle actions during both the bending and extending motion of the swing phase is obtained.

One point remains, however, which needs further explanation. At the rear end of the swing, where the bending motion stops and the extending motion begins, the fluid flow within the hydraulic system is temporarily reduced to zero and, as a result, no frictional forces can develop. This looks like a serious limitation of the hydraulic swing control principle because, on the basis of the pendulum analogy, we should expect that the forces involved reach a maximum at the reversal point of the swing. However, myographic studies carried out by the University of California⁷ revealed the somewhat surprising fact that the quadriceps group, which would be the one to produce these forces, is almost inactive in the majority of subjects during that part of the swing phase, even at higher cadences. The dilemma resolves itself, however, if we consider that the influence of the gravity force on the lower leg, which we have been neglecting so far, reaches its maximum while the lower leg is going through that part of the swing phase. Since the gravity force does not increase with the square of the cadence, but remains constant, one should expect that the lower leg swings slightly higher at higher cadences. This is being confirmed by measurements carried out by New York University,⁸ which show the heel rise of normal subjects at various cadences. The same is the case in above-knee prostheses equipped with the hydraulic swing control system.

Acknowledgments

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Academy of Sciences, New York, N. Y., as well as for the help given by the Prosthetic Devices Study group of New York University, New York, N. Y., and by the Basic Research group of the University of California, Berkeley, Calif.

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REACTIONS TO LOSS OF LIMB: PHYSIOLOGICAL AND PSYCHOLOGICAL ASPECTS

By William B. Haber

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In our work with the physically handicapped, as in current work with the mentally ill, we find a curious dichotomy: those who deal with the physical or physiological aspects often profess little interest in the psychological factors and, conversely, psychologists and psychiatrists tend to neglect physiology. I believe that the proper study of the amputee requires both physiology and psychology; the two approaches are complementary rather than mutually exclusive.

With this in mind, the work I have done on effects of amputation has been divided into three parts: (1) sensory changes in the stump, (2) appearance of phantom sensations, and (3) psychological aspects of loss of limb. In a survey of the literature, I had already found that studies of sensory functions in amputation stumps are quite rare (in contrast to the numerous descriptions of changes in somatosensory functions after brain damage). Likewise, although there is no dearth of literature describing the nature of phantom limb (the illusion of continued presence of a limb or parts of it, after amputation), the phenomenon itself remains puzzling. Further investigation showed only meager reports in the literature on the psychological effects on the amputee.

Sensory Changes

In 1949 Teuber *et al.*¹ investigated the problem of reorganization of sensory functions following amputation. They found, in 38 men with above-the-knee amputations that two-point discrimination was better on the stump than on corresponding areas of the sound limb. Katz,² in 1920, published similar data on several forearm amputees. Teuber *et al.*³ predicted their data would show that "central readjustment . . . imparts to the stump some of the functional characteristics of the amputated limb" (p. 156). In addition, Teuber and his co-workers discovered "trigger-zones" on stumps in their group of amputees and, when these zones were tapped or rubbed, the subjects related that the produced tingling "spread" into distal portions of their phantom limb. The map of the distribution appeared to correspond with the dermatomal arrangements rather than with the peripheral nerve representation.

In my own work⁴ I extended these data on stump sensitivity by measuring point localization and light-touch threshold, in addition to two-point discrimination. Specifically, my purpose here was to validate the general hypothesis that increased stump sensitivity follows amputation, and that such changes can be explained by postulating central rather than purely peripheral factors.

In normal limbs, tactile thresholds are smallest in distal regions of the body

and high in proximal parts; yet, although distal parts (finger tips) have large representation in the central nervous system and proximal areas (arms) have smaller representation, we cannot ascribe a proximodistal gradient in sensitivity to central factors alone, since peripheral receptors are dense in distal regions and less so in proximal areas. The study of amputees gives us a unique opportunity to investigate the relative importance of central and peripheral factors in making proximal parts less sensitive than distal parts of the body.

The results of my study showed stump sensitivity in 24 male veterans (World War II) with unilateral above-elbow amputations (12 right, 12 left) exceeded that of homologous parts of the normal arm for 3 aspects of somatic

TABLE 1
ANALYSIS OF DIFFERENCES OF TACTILE THRESHOLDS: INTACT LIMB VERSUS STUMP

	Intact limb			Stump		
	<i>M</i>	<i>S</i>	vs. <i>M</i>	<i>S</i>	<i>F</i>	<i>t</i>
(A) Light-touch threshold	3.37	0.11	2.42	0.30	1.33	17.27*
(B) Two-point discrimination . .	60.70	9.57	42.86	7.68	1.55	10.37*
(C) Point localization	14.07	3.55	6.34	2.78	1.62	15.77*

* $P < 0.001$

sensation, namely, light touch (tested with modified von Frey hairs), two-point discrimination, and point localization. Thresholds were obtained in counterbalanced order in 2 regions of the stump (2.5 cm. from the tip and 2.5 cm. from the head of the humerus) and in the 2 homologous regions of the intact limb. Corresponding areas in both intact arms of 12 additional World War II veterans without loss of limb were tested as controls.

The means and standard deviations of each of the tactile thresholds for intact limb versus stump are given in TABLE 1. The average touch threshold (A in TABLE 1, measured in log milligrams necessary to bend the graded Nylon filaments) was 2.42 for the stump in our 24 amputees and 3.37 for the intact arm. The average two-point discrimination threshold (B, the minimum distance in millimeters at which 2 compass points were perceived as 2, and not 1) was 42.86 on the stump and 60.70 on the intact limb. Finally, the average error of point localization (C, also measured in millimeters) was 6.34 on the stump and 14.07 on the sound limb. Variance ratios and *t*'s were computed for each comparison between sound limb and stump. All differences were significant at a level of confidence better than 0.001. Furthermore, in each individual, the skin on the stump showed significantly lower thresholds for tactile stimuli on all 3 measures—light touch, two-point discrimination, and point localization.

Alteration of performance was found over the entire stump and was not restricted to the distal portion. FIGURE 1 shows the thresholds on the distal

and proximal regions of the stump (areas 1 and 2) and in the corresponding distal and proximal regions of the sound limb (areas 3 and 4). The touch thresholds, in log milligrams, are shown at the right of the diagram. At the $\frac{1}{10}$ per cent level of confidence, stump thresholds were significantly better than sound-limb thresholds. The distal stump threshold (area 1) also was significantly better than the proximal stump threshold (area 2) at the 1 per cent level, but there was no significant difference between the distal threshold (area 3) on the intact limb and the proximal threshold (area 4) on the intact limb.

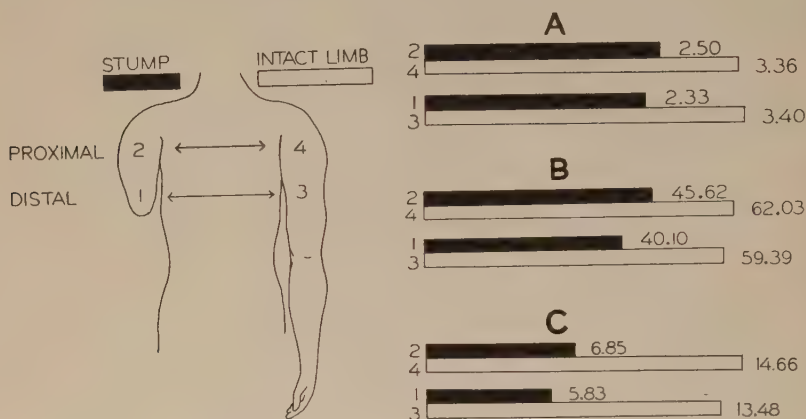


FIGURE 1. Mean thresholds on proximal and distal portions of stump and intact limb. (A) Light-touch threshold, in log milligrams; (B) two-point discrimination, in millimeters; (C) point localization, in millimeters.

Similar results were obtained for two-point discrimination. Again, comparisons of stump to sound limb thresholds in millimeters were significant at the $\frac{1}{10}$ per cent level, while the distal threshold (area 1) on the stump also was significantly better than the proximal (area 2) at the 1 per cent level; again, there was no significant difference between area 3 and area 4, the distal and proximal regions on the intact limb.

Likewise, comparisons for average errors of point localization, also measured in millimeters, once more point up the superior performance of the stump and the proximodistal gradient, which was significant at the 5 per cent level for the stump (1-2) but failed to reach significance for the sound limb (3-4).

Comparisons of thresholds on right stumps with those on left stumps showed no significant difference, nor did right differ from left intact limbs. The thresholds of the sound limbs of our amputees did *not* differ from either arms of our 12 control subjects (without amputation), but all stump thresholds (right or left) were better than corresponding control thresholds at the $\frac{1}{10}$ per cent level of confidence.

The steeper proximodistal gradient on the stump suggests that the distal portion of the stump has taken over some of the sensory functions of the hand.

Another singular finding supporting this suggestion shows a significantly smaller number of errors of localization on the stumps of men with "telescoped" phantoms than of those with "extended" phantoms. FIGURE 2 shows some of these extended phantoms drawn by 12 patients and a few of the telescoped phantoms drawn by the remainder (12) of the group. The term extended phantom covers those instances where the subject reported his

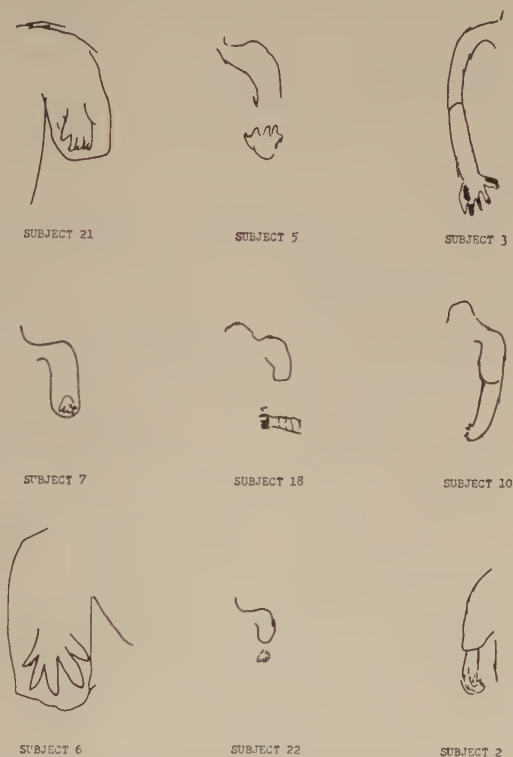


FIGURE 2. Drawings made by 9 amputees. "Telescoped" (subjects 21, 7, and 6) and "extended" (with gaps, subjects 5, 18, and 22; without gaps, subjects 3, 10, and 2).

phantom outside his stump, while telescoped refers to those reports where the phantom hand is either completely inside the stump or with fingers partially protruding from the stump. TABLE 2 shows the results of this comparison in terms of improvement scores (average gain, in per cent, of stump over sound limb). The difference was significant at the 1 per cent level of confidence for point localization. The difference between the means of the thresholds for light touch and two-point discrimination was *in the same direction*, but did not reach significance at the 5 per cent level. Sensory improvement in the stump and the finding of greater improvement of tactile discrimination in telescoped phantoms suggest that reorganization of function and tactile discrimination depend on central factors.

TABLE 2
ANALYSIS OF DIFFERENCES OF TACTILE THRESHOLDS BASED ON IMPROVEMENT SCORES
(MEAN PER CENT) TELESCOPED VERSUS EXTENDED PHANTOM

	Extended vs. Telescoped		<i>t</i>
(A) Light-touch threshold	25.6	30.6	1.80
(B) Two-point discrimination	27.5	29.9	0.53
(C) Point localization	49.2	64.2	2.86*

* $P < 0.01$

Phantom Limb

A further study of phantom limb phenomena was implicit in my research.⁵ Practically every person who loses a limb or part of an extremity experiences the same curious sensation—that the lost limb is still there. Mitchell⁶ used the term phantom limb to describe a phenomenon known since Paré,⁷ who first reported painful phantoms in 1552. For centuries, attempts have been made to explain phantom limbs, for obvious reasons.

In the first place, there are the theoretical aspects of such work; systematic study of groups of amputees may help us to understand mechanisms of normal sensorimotor functions and the ways in which we normally experience the movable parts of our body. Furthermore, there are the obvious practical reasons for a study of phantom limbs; understanding their etiology may help us find a successful cure for painful phantom. Alleged cures have been percussion, electric stimulation of stumps, anesthesia, reamputation of stumps at higher levels, removal of neuromas, cutting peripheral nerves, dorsal root sections, and even blocking or removal of sympathetic nerves and ganglia. Some have attempted resection of sensory cortex, electric shock, or frontal lobotomy, while others have tried ultrasound, Chinese acupuncture, psychotherapy, and ataraxic drugs. None of these professed cures have proved completely effective for any length of time; at least, empirical proof for the adequacy of any therapeutic approach is still lacking. In addition, methodical knowledge of phantom limb phenomena should be useful to the prosthetic manufacturer and helpful for successful rehabilitation of amputees. Finally, phantom limb information is necessary for an empathic comprehension of the amputees' deep emotional responses.

Theories. Essentially, there are three theories to account for the etiology of phantom limb, those assuming a central, peripheral, or a mixed origin. According to the central theory, the phenomenon originates in the central nervous system. This could be due to either of two hypothetical mechanisms—learning or innate dispositions. According to the version of the central theory that stresses learning, the central nervous system “learns,” from birth onward, to experience sensations arising from different body parts, and to localize these sensations. As a result, we remember these feelings even after loss of a part, since it still belongs to our acquired “body image.” Alterna-

ively, the central nervous system, through innate (structural) organization, "expects" certain sensations from parts of the body. The peripheral theory attributes phantoms to sensations aroused in nerve endings in the stump. Finally, the mixed theory combines both peripheral and central factors to account for the phantom sensations. In contrast to these physiological theories, there are those stressing so-called psychogenic factors, by invoking either certain specified neurotic mechanisms or general psychoanalytic interpretations. Most of the available evidence advanced for the central theory depends on clinical descriptions, heuristic conjectures, and the claim that cerebral resections and parietal lobe infarction can abolish the phantom. Evidence from studies on phantoms in paraplegics,⁸ and recent observations on lepers who have lost parts of limbs, fingers, or noses by absorption or surgery⁹ complicate the problem further. Proponents of the peripheral theory attempt confirmation by claiming direct relationships of phantom sensation to sensory stimulation of the stump, and relief of pain either by removal of neuromas or by severance of dorsal roots. Those who support mixed theories believe that the phantom is not due completely to central factors, but that the sensory impulses from the periphery are integrated centrally in a special way.¹⁰ To choose between the different theories is difficult and perhaps premature. We need more empirical work, especially since quantitative studies of phantom limb are limited. Katz,¹¹ Henderson and Smyth,¹² Cronholm,¹³ and Teuber *et al.*^{3*} have contributed valuable information. A brief resume of some of my own work follows.

Material and methods. The amputees were the same 24 male World War II veterans with unilateral above-elbow amputations whom I had tested for evidence of reorganization of tactile functions. After sensory thresholds were obtained on the stump and sound limb, each subject answered 56 questions (in an informal sitting lasting 20 to 30 min.) regarding his phantom sensations. The examiner avoided the use of the term phantom limb unless the subject introduced the term. The ages of the men ranged from 27 to 43 years, with a mean of 33; I.Q.'s ranged from 104 to 141, with a mean of 119 (by an abbreviated Wechsler-Bellevue adult intelligence scale). The Rorschach test,¹⁴ individual form, was administered to all amputees. At the conclusion of testing, each of the 24 subjects† made a pencil drawing of his phantom limb.

Results. All 24 men reported phantom sensations, with only one describing it as sometimes painful. The majority described the feeling as "tingling," "pins and needles," "as if asleep," "vibrating," or "electricity." Itching was reported by 7 men who, at times, attempted to scratch some phantom part. Coexisting sensations of throbbing, pulsating, warmth, tenseness, clenching, clutching, gripping, and numbness also were reported. One sub-

* I am grateful to Hans-Lukas Teuber of the Psychophysiological Laboratory, New York University-Bellevue Medical Center, for his persistent helpful criticisms, inspiration, and inimitable advice. Teuber's previous experience with amputees made him a constant and particularly helpful source of information.

† I am grateful to James Cohen and Julius Feig, of the National Amputation Chapter, New York, N. Y., for their cooperation and, in particular, to the amputees who served as subjects.

ject volunteered "a tingling sensation, tingling in finger and thumb. Compact and smaller in size all around, still feels like a hand. Pins and needles effect." Another said, "ticklish mostly, phantom hand as though it were there—feel tips of fingers—pins and needles. The ring on my finger feels tight and bent. Pins and needles and drawing sensation—gripping too." Still another said, "I can feel my hand. I can't get thumb out—hand is dangling below stump. Pins and needles, it goes to sleep on me." One man stated "a certain numbness, sometimes sensation of itching. But if you face realities, there is no hand there. However, don't let anybody tell you, like M.D.'s, that's in your mind. No figment of imagination. The sensation—like burning from a match and yet asleep, a combination of these two." Another reported ". . . the hand is right in front of my face. I'm looking at it."

In general, the outstanding feature of these reports is their marked uniformity, which makes it difficult to attribute the origin of the phantom to unusual conditions of the stump or special conditions before or after amputation. An analysis of the nature of the original trauma of presence or absence of gangrene, or various other factors connected with the amputation, reveals a great variety of conditions before and after trauma, a variety in marked contrast to the relative uniformity of phantom sensations.

All of our patients except 2 reported shrinkage of the phantom and varying amounts of decreasing distance between phantom fingers and the tip of the stump. We have mentioned already that 12 of the men reported phantoms in the stump (telescoped) and 12 reported that their phantoms seemed "extended in space." Five men claimed that a gap remained between "proximal" parts and distal portions of their extended phantoms; 7 reported extended phantoms without a gap. It will be recalled that better stump sensitivity was found in amputees who reported telescoped phantoms, as compared with those whose phantoms were described as extended.

The gradual fading of a phantom takes place in a definite sequence; for example, proximal portions vanish first, then intervening areas, and finally the distal parts. Likewise, the distal regions are felt most vividly, even soon after amputation; the elbow is sometimes present, the forearm rarely, the upper arm almost never. The rank order of parts, in terms of frequency reported on a 6-point scale of vividness, corresponds closely to the size of cortical representation allotted to these parts. Fingertips, thumb, and all 5 fingers were ranked as most vivid with almost equal frequency; next in order were palm, wrist, and back of hand; forearm and elbow were infrequently mentioned and were least vivid.

My observations show that the range of movements in the phantom is more restricted than the awareness of stationary phantom parts. In other words, the ability to "move" phantom parts fades faster than the ability to experience these parts. Ability to call up phantom sensations at will was reported by 21 amputees (88 per cent), while 12 reported the ability to move phantom parts, although this movement was limited to the distal parts. Five of the 12 could move the fingers in their telescoped phantoms, while 7 reported movements in the extended phantoms. All of these men could make a fist,

and 7 maintained that flexor movements were easier to make than extensor; the position of the phantom also was reported as slightly flexed. None of the subjects with telescoped phantoms claimed to be able to penetrate solid matter with their phantoms; by contrast, 6 of the 12 who had extended phantoms reported they could move the phantom through solid objects. In the remaining 6 cases the extended phantom temporarily disappeared whenever the stump was moved close to some solid object.

Spontaneous "reaching" movements often appear in phantoms immediately after amputation, and 9 of the 21 who reported such inclinations said this tendency still persisted. As one subject said, "I often attempt to catch a ball with my phantom." Such illusory movements are related to the finding that phantoms, under certain conditions, may change positions, whether extended or telescoped. When the experimenter made a sharp perpendicular movement with a ruler through the air near the stump, 4 men said their extended phantoms recoiled closer to the stump, while 4 with telescoped phantoms felt a temporary lengthening of their phantom. One amputee stated he felt a desire to "pull away"; another wanted to "grasp the ruler."

As we have stressed, we found no significant relationship between the characteristics of the phantom and the conditions at the time of the loss of the limb, either in the position of the phantom or in the amount of pain. However, there were 8 cases (7 had extended phantoms) where similarities appeared between the posture of the phantom and that of the limb prior to the loss. One patient said, "the hand is right in front of my face"; previously he had described how he had attempted to protect his face from flying shrapnel. Even more interesting were the reports of 3 men who claimed they felt imprints of rings and one man said, "I know . . . because I had two watches on my wrist and . . . I was irritated because they were not returned." He related that he continued to feel the pressure of the watches on his phantom wrist.

There was no relation between the wearing of an artificial limb and the location or vividness of the phantom, although the prosthetic devices were quite varied. Eighteen wore a prosthesis; of these, 7 wore a mechanical hook or glove, 9 wore a nonfunctional cosmetic glove, and 2 sometimes wore a functional and sometimes a cosmetic prosthesis. Neither did we find a relationship between vividness of the phantom, or type of prosthesis worn (functional or cosmetic) with better sensitivity on the stump. Prosthetic devices do not appear to influence reorganization of tactile functions on the stump.

Psychological Aspects of Loss of Limb

Finally, I propose to discuss a few of the findings of the Rorschach test and related data delineating some of the psychological aspects of loss of limb. To our knowledge, Rorschach studies on amputees are rare. One study was based on 4 protocols and another on 12 cases. However, 1 intensive investigation of the personality characteristics of 48 above-the-knee amputees showed differences between 12 efficient and 12 inefficient users of a prosthesis.¹⁵ I used the Rorschach test because many clinicians believe it is the best single instrument for assessing personality structures and, specifically, for

evaluating emotional adjustment. I hoped to obtain a series of indices that might bear on the patient's attitude toward his disability. I obtained the Rorschach protocols and transmitted them, unscored, to 2 psychologists, who worked independently of the examiner and of each other. Neither of these psychologists was told anything of the subject's clinical history. One psychologist* prepared a psychogram, while the other† classified the protocols, after scoring, into clinical syndromes and basic character structures.

The results showed significant differences between indices of "adjustment" scores among groups of amputees. Reactions to color on the Rorschach have been interpreted as expression of affect. When the number of $CF + C$ responses is greater than the number of FC responses, an inadequate emotional adjustment in a self-centered person is the usual interpretation. On the other hand, $FC > CF + C$ is said to indicate adaptability and conformity, an index of self-control. Six of the 7 persons who used a functional prosthesis produced $FC > CF + C$; the other subjects' response's, yielded $FC = CF + C$. This preponderance of form over color responses is compatible with the view that men using functioning prostheses show greater self-control than those using nonfunctioning (purely cosmetic) devices. In fact, 6 of the 9 amputees who chose a cosmetic prosthesis produced $CF + C > FC$, and 2 men gave $CF + C = FC$, while 1 produced no color responses. In addition, there were 6 men who never used a prosthesis; of these, 4 produced $CF + C > FC$, 1 gave $CF + C = FC$, and 1 gave no color responses. This accounted for 22 men. The twenty-third man used a hook, but kept it in his pocket at all times. He produced $CF + C = FC$. The twenty-fourth man used a cosmetic prosthesis "to go out" and a functional one for "work." He produced $CF + C > FC$. The results seem to demonstrate a positive relationship between adjustment and type of prosthesis adopted.

Inspection of the data also made it possible to consider the psychoanalytic view of phantom limb. The analyst leans heavily on the concept of denial, for example, that amputees are unconsciously unreconciled to the fact that they have a missing limb. Mahler-Schoenberger and Silberpfennig¹⁶ found that 9 of 12 patients with phantom sensations gave overwhelming anatomy responses in the Rorschach. These investigators interpreted their data as indicative of a refusal to relinquish body image integration. Normals who produce records of average length give a single anatomy response. Our 24 subjects gave a total of 39 responses. The tendency is in the direction of a greater than average number of anatomy responses when we consider that 14 subjects gave the 39 anatomy responses even though 10 gave none.

A person who loses a limb experiences psychological trauma as well as a physical injury. The psychological meaning of the loss may determine the kind of defense mechanism an amputee may adopt in reacting to his changed appearance. Recent papers^{17, 18} on postoperative reactions following loss of

* I am indebted to A. Levine of Hillside Hospital, New York, N. Y., who scored the Rorschachs of each subject.

† I am grateful to Fred Brown of Mount Sinai Hospital, New York, N. Y., for classification of the Rorschach protocols and for his insightful analysis of the character structure of the 24 subjects.

limb stress (1) attempts to master the environment to compensate for loss of self esteem, (2) exaggeration of independence achieved through denial of disability, and (3) depression and mourning for the lost extremity. A composite analysis of the Rorschach protocols of our 24 amputees is given in the summary written by Fred Brown: "Levels of aspiration in general are quite high, with maximized organizational drive and strong success goals. This group impresses one with the extent to which *ego functioning* is utilized in conjunction with an aggressive self-will. The regressive cravings . . . are rejected through (1) *denial* of impairment, (2) overemphasis upon a masculine facade, and (3) a constrictive defense against anxiety and depression. Increased feelings of rejection, isolation and inadequacy re-mobilize *denial through action* . . . overcompensating to the extent that they are operating on a higher level than in the pre-amputation period."

From an experimental standpoint, it would have been more satisfactory if the interpreter did not know beforehand that the Rorschach protocols had been obtained from amputees. To test these intriguing interpretations fully, we need a repetition of this appraisal by someone who is kept unaware of the origin of the Rorschach protocols. Regardless of how much or how little we want to rely on projective test material in evaluating the psychological reactions to loss of limb, it should be evident that the responses of amputees can be used to validate the projective tests! We consider it most remarkable that the Rorschach records (scored "blindly") should be able to differentiate wearers of functioning prostheses from those who wear cosmetic devices. This lead should be pursued further. In the meantime it is apparent that psychological studies of amputees can be potentially as precise as those based on physiological methods, and that the physiological studies, in turn, are psychologically relevant.

Summary

Twenty-four male veterans (World War II) with unilateral above-elbow amputations (12 right, 12 left) were interviewed and tested systematically to obtain (1) tactile thresholds on their stumps, (2) data on phantom limb, and (3) information on personality adjustment of the amputee. The results indicate the following:

(1) Stump sensitivity exceeded that of homologous parts of the sound limb for light touch, two-point discrimination, and point localization.

(2) Shrinkage, folding, and stretching of the skin on the stump do not appear to influence stump sensitivity.

(3) Sensitivity was better on the stumps of men with telescoped phantoms than in those reporting extended phantoms. This finding suggests central rather than purely peripheral factors in the origin of phantom limbs.

(4) The similarity of phantom-limb sensations, despite dissimilar conditions in the stump, or special conditions before or after amputation, also point strongly to a central theory.

(5) The phenomena of (a) telescoping and (b) gradual fading and persistent vividness of parts, according to their cortical representation, favor central factors.

(6) Illusions of motion in distal parts of the phantom, ability to call up phantoms at will, and superadded sensations cannot be attributed to peripheral factors.

(7) There was no significant relationship between the wearing of an artificial limb and the dimensions, quality, or vividness of the phantom sensations.

(8) The Rorschach test apparently can differentiate between wearers of different types of prostheses (functioning versus cosmetic). This finding adds weight to the belief that personality differences enter into the choice and use of prosthetic devices. In addition, these observations suggest a single and direct way of testing the validity of the Rorschach technique and related projective methods.

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THE BODY IMAGE AS RELATED TO PHANTOM SENSATION: A HYPOTHETICAL CONCEPTUALIZATION OF SEEMINGLY ISOLATED FINDINGS

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The effects of amputation are not merely physical, but psychological as well. It has been noted clinically that appreciable changes take place in the body image of the amputee. Amputation results in drastic reduction of the positive aspects of the self concept or body image. According to psychoanalytic theory, the amputee experiences feelings of "castration," of being "deprived" or "half-a-man," instead of being an intact or whole personality.

Self-Image

Schilder's (1950) concept of the body image is relevant to amputation. The body image, or self concept, as applied to amputees, has emphasized the negative aspects of changes. The amputee finds it difficult to incorporate negative values into his self concept, since relinquishing positive traits is seldom a pleasant experience. It should be noted, however, that any change in the body image, even a very positive one, is difficult for the personality to assimilate. For example, individuals who lose much weight, slimming down to acceptable architectural form as advocated by Hollywood, often find it difficult to assimilate the new, improved image staring at them from the mirror. They have been so accustomed to seeing themselves as unesthetic, bulky individuals that they do not readily integrate the new image into their personality. We may conjecture that the great tendency of these people to regain weight rapidly is not due merely to a neurotic tendency to recapture the secondary neurotic gains they have lost. That is, it is not due merely to their desire to flee from their new responsibilities as slim individuals who now have no excuse to refrain from competing with others on an equal basis. It is our feeling that a perceptual factor plays a major role. The individual cannot reconcile the image of obesity that has become his heritage, his bulwark against the world, his self concept, with the new personality perceptually alien to his entire self system. Since the mind always strives for clarity, for a structured field, for elimination of ambiguous situations, and for a clear field of vision, the contradictory self images or self concepts are almost intolerable. The more established image gains ascendancy by prompting the individual to regain the lost weight.

It is very difficult, therefore, to assimilate a new, positive image, as well as a negative change, of oneself.

Another example is the instance of plastic surgery prematurely performed to eliminate disfigurement (a better example, since the visceral drives leading to neurotic reinstatement of the poorer image are absent). Psychologists have found that, unless intensive psychotherapy is instituted, the improved

cosmetic and esthetic facial appearance is not readily accepted by the patient. It is difficult for the formerly ugly person to accept the new, esthetic constellation of features. The latter is a stranger to him. Many women who have become cosmetically more desirable following plastic surgery often feel that their now numerous beaux and admirers do not love them really for themselves.

In summary, when considering the problem of psychological effects of amputation, the positive as well as the negative changes of the self image must be given due weight.

Phantom Sensation

In considering the problem of phantom sensation as discussed by Haber, his paper notes a number of isolated facts that do not seem to form a cohesive, integrated whole. I believe an analysis of phantom sensation, neutral and painful, enables us to posit, at least as a preliminary approach, a theoretical conceptualization that may account for the isolated findings mentioned by Haber. Prior to considering our conceptual hypothesis, it should be emphasized that the studies strongly support a central or at least a central-and-mixed origin of phantom sensation, rather than a purely peripheral one. However, it would be inaccurate to claim that only neurological factors are involved in the experience of phantom pain sensations.

Preliminary studies on small samples at the Prosthetic Devices Study support the contention that psychological factors play a considerable role in the production of phantom sensations. Analysis reveals a strong tendency for those experiencing painful and uncomfortable sensations to obtain greater insecurity scores on the Maslow S-I Inventory than those amputees with few or no phantom sensations. A clinical evaluation of our selection battery supports the contention that the personality make-up of an individual contributes to his perception of phantom pain and limb phenomena (we define pain as not merely intractable pain, but any annoying or painful sensation). With this in mind, we can proceed to our theoretical conceptualization. The following findings should be underscored.

There are three groups of amputees: (1) those who experience no phantom-limb sensations, (2) those who experience telescoped or shortened limb, and (3) those who experience an extended limb. It is posited that the first group represents those who, in the course of time, have come to terms with reality by accepting (1) the loss of their limb as well as (2) loss of sensation. The second ("telescoped") group represents individuals who have compromised with reality. They have been willing to relinquish the extension of the original limb, but not the sensation involved. The individuals of the last ("extended") group have been unwilling to compromise with reality on an unconscious, primitive level. They insist upon retaining both the phantom sensations and the original extension of the absent limb. Thus, individuals perceiving no phantom sensations are individuals who have adjusted themselves to the reality situation of having no limb. They have succeeded in reorganizing the self image in terms of realistic factors, rather than in terms of wishful, narcissistic fantasy. Individuals with extended limbs refuse

to accept reality or to compromise with it. They insist on maintaining their former self image despite the evidence facing them. This is reminiscent of the mechanism of denial in some individuals. The human mind has the faculty of denying not merely evidence that is hazy, but evidence that is clear and decisive. Amputees with telescoped limbs have compromised with reality. They have accepted the physical loss of extension, but insist on the presence of the limb, albeit in abbreviated, telescoped form.

The flexibility of perception of reality is illustrated in the case of some amputees with telescoped limbs who, when fitted with prostheses, feel their phantom limbs extending and coalescing with the prostheses. In these cases it is suggested that the prosthesis, since it provides "extension," reactivates the suppressed desire for the lost limb. Seemingly, the narcissistic desire to maintain a lost limb operates to make the prosthesis reminiscent of that limb and brings to the fore the previous intact body image.

With this introduction, we are now prepared to understand some isolated findings and perhaps unify them in one cohesive conceptualization. Haber found that (1) telescoped limbs are more often the rule than extended limbs; (2) flexor sensations are more prevalent than extensor sensations; and (3) telescoped limbs are superior to extended limbs, in terms of two-point discrimination, point localization, and lower threshold. Proximal regions increase in sensitivity not explicable in terms of peripheral nerve endings. Evidently, central neurological and psychological factors are involved. What are they, and how can one parsimonious statement unify these isolated facts?

In attempting to answer this, it is necessary to analyze the nature of painful phantom sensation. There are two ways of approaching the problem. The first may be the hypothesis that phantom sensations in amputated limbs are a result of the amputee's wish to retain his limb because of narcissistic demands. Since he retains his limb, his neurotic problems are projected to the limb, resulting in phantom sensation. The second hypothesis is that pain (or an uncomfortable sensation, such as tingling) has a functional value. The amputee has pain not as a manifestation of neurosis alone and not as a consequence of maintaining his limb: rather, the pain serves the function of convincing him that he has the limb. The painful sensations thus are employed by the amputee to allow him to reason as follows: "I have pain. Since I have pain in the area where my limb was, I must still have the limb." This specious reasoning, a reversal of the reasoning of the first alternative, is of course on the primitive, unconscious level, which certainly can utilize the mechanism of denial as employed by some disabled individuals even in less ambiguous situations, such as blindness. As mentioned by Haber, Rorschach findings in amputees suggest that "denial" (of loss of limb) through activity is a preponderant compensating mechanism.

We may now proceed with our conceptualization. If we accept the second hypothesis, of the "functional service of pain," we can understand (1) why flexor sensations usually are more prevalent than extensor sensations; (2) why there is a tendency toward telescoped rather than extended limbs; and (3) why there is a superiority of the proximal regions in terms of two-point discrimination, localization, and lower threshold.

(1) In the flexor position, one part of the limb, such as fingers, is in greater contact with the other parts than in extensor position. Therefore, by having a flexor sensation (such as cramping, or of fingers digging into the skin) the individual is rationalizing the presence of the limb by making it painful, especially in terms of greater body contact.

(2) In telescoping a limb, the amputee brings the phantom hand or foot nearer the existing physical stump. Thus there is an interaction between the physically real stump and the phantom limb. Consequently it is easier to maintain and to retain a telescoped hand because, although it is a phantom, it is still made to be in touch with a physically real stump. In its extended state, the reality factor obtrudes; it is not so easy for the amputee to rationalize the phantom when it is so distant from the nerves in the stump.

(3) Since the phantom limb is interacting with the physical stump on psychological and neurological bases, the proximal regions now become more sensitive because the amputee has made them so. This hypothesis can be tested by having the stump anesthetized either prior to the telescoping of the phantom limb or after the telescoping has taken place. In the first instance, perhaps anesthetizing a portion of the stump for an extended period of time will either prevent telescoping to the stump or will facilitate telescoping beyond the anesthetized area, closer to the trunk. In the latter case, perhaps, a telescoped limb will disappear and become extended again, since the source of interaction is anesthetized; or the telescoping also will proceed beyond the anesthetized area, closer to the trunk. Our theory can thus be subjected to an experimental test. Schilder (1950, p. 65) reports that cocaineization of the nerves made the phantom disappear. In future controlled experiments, the anesthetic should be infused without the subject's knowledge, and placebos should be used as controls.

Dreams and Phantom Sensations

As a clinician concerned with psychotherapy, I have found it interesting to see the resemblance between phantom sensation and dreams. The dreams are often elusive, vague, evanescent, subject to distortion and change. The same characteristics seem to mark the amputees reporting phantom sensations. The similarity between them again supports the psychological nature of these phenomena.

Practical Implications

If our hypothesis about the self concept is valid, then the following considerations are in order. In providing artificial limbs for individuals, there is a tendency to provide maximum function with minimum complexity of the prosthesis. If it were really possible to make an artificial limb as functional, as painless, and as comfortable as the natural one, the amputee would be able readily to integrate a simple wooden or plastic prosthesis in his self concept and body image. However, since even the best prostheses cause discomfort and stimulate awareness of the loss, perhaps a different approach to prosthetics is in order. The amputee has lost an admirable and complicated structure. Can a simple prosthesis, a piece of wood or plastic, really ever

satisfy the amputee as a replacement for a limb? Do we not hear amputees joking about such things as the "splinters" in their legs. It seems to me that a complex prosthesis, such as a hydraulic leg, the mechanism of which in some ways resembles the complexity of a real leg, may be more readily integrated into the body concept of the amputee. Give him a wooden or plastic leg, and he feels that it is artificial. Give him a well-functioning complicated mechanism and, to some extent, you may approximate the complexity of the natural limb he has lost.

As another practical implication, consider that at present an appreciable period of time must elapse between the amputation and fitting. This involves the amputee in a conflict between the concept of himself as a whole person and his amputated state. The longer the period of time between amputation and fitting, the more difficult it will be to restore the original self image of the amputee, since neurotic mechanisms will operate during this waiting period. If it were medically feasible to fit the amputee immediately after amputation (although the leg would undoubtedly require changing because of shrinkage and other factors), the feeling of emptiness on the part of the patient would not develop to the extent that it presently does. The amputee would learn to integrate his artificial limb before being compelled to make a revision of the self concept from nonamputated to amputated—from amputated to "not whole"—and then again from not whole to "whole-with-prosthesis." Immediate fitting would eliminate the difficult transitions and enable the amputee to retain the integrity of wholeness and of his former self image.

Acknowledgments

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COMMENTS ON BIOLOGICAL ASPECTS OF AMPUTATION

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The human disabilities discussed in this monograph are all characterized by neurological dysfunction. This is most evident in the instances of blindness and deafness, as these conditions usually result either from impaired transmission of stimuli or from anatomical malformation. Similarly, syndromes classified as neuromuscular dysfunction are caused by damage, disease, or malfunction of some portion of the nervous system. However, the neurological loss involved in amputation may be obscured by the actual physical loss or absence of a body member.

All of the papers presented in Part I have been concerned, at least partially, with neurological dysfunction. Sensory loss following amputation and the subconscious characteristics of purposeful movement has been discussed. Haber has discussed the development and regeneration of sensibility in the post amputation stump, phantom-limb phenomena, and phantom pain. In a somewhat different vein, Mauch has pointed out that more satisfactory prostheses could be designed if we could tap nerve endings and thereby transmit and receive a large number of signals to and from the body and prosthesis.

The studies made by H. Head and his associates (reviewed by Best and Taylor, 1945) on loss and return of sensibility in the arm following experimental section, at the elbow, of the radial nerve and of the cutaneous portions of the musculocutaneous nerve demonstrate a pattern of neurological change similar to that following amputation. Epicritic sensibility (light touch, point localization, two-point discrimination, and fine grades of temperature discrimination) disappears completely in both instances. Head found that return of epicritic sensibility first appears approximately one year following neural section and is not completed even after a second year elapses. Although these phenomena have not been studied in the same manner for amputees, they seem to be in general agreement with the findings reported earlier in these pages.

Protopathic sensibility (pain and temperature) is concerned with a more primitive and diffuse class of sensation, characterized by relatively high threshold values and discomfort. Protopathic sensibility is particularly noticeable in the absence of the epicritic type. Return of protopathic sensibility commences about six weeks following section of the sensory nerves and is completed within six months. A somewhat similar pattern is found in amputees, and fitting of a prosthesis is usually delayed, because of tenderness and pain, until six months after amputation.

Deep sensibility (pain, pressure, and sense of position or movement) remained unchanged following neural section. Similarly, deep sensibility is retained after amputation, except for limitations in position sense associated with the loss of one or more joints.

If there is a genuine relationship between the neurological concomitants of sensory neural section and amputation, then the following hypotheses may be advanced: diffuse pain, phantom pain, and phantom limb phenomena are characteristic of protopathic sensibility and are indicative of the absence of epicritic sensibility. The disappearance of diffuse and phantom pain, and the telescoping of the phantom limb result from the suppression of protopathic sensibility and indicate the (partial) regeneration of epicritic sensibility. A substantial return of epicritic sensibility may be expected during the second year following amputation. This may be a consideration for increasing the utility of prosthetic equipment by training the amputee to utilize these added sensory cues.

It was pointed out that whereas walking is instinctive, manual activities are learned skills. A nonamputated person develops patterns of function that involve specific series of synaptic junctions. When amputation precludes the performance of certain activities, the central and unaffected peripheral synaptic junctions concerned remain intact regardless of the level of cerebral acceptance. Accordingly, the amputee must learn new patterns of body function on both conscious and subconscious levels if he wishes to maintain his level of performance. If this neuromuscular rehabilitation has developed substantially before a prosthesis is fitted, it follows that the reeducation process must be repeated after fitting.

The utilization of artificial limbs in general, and of prosthetic arms in particular, is limited by contradictory factors that complicate the successful fitting of a prosthesis. The most cosmetic prosthetic components frequently do not afford the maximum function. An artificial hand, for example, is more cosmetically acceptable than any hook, but its bulk obscures visual cues and greatly reduces the effective prehension of very small objects.

It has been suggested that it would be desirable to fit a prosthesis immediately after amputation. However, a minimum of three to six months usually is required for healing, stump shrinkage, and reduction of sensitivity before a level that permits satisfactory fitting is achieved. This time lapse is of sufficient duration to allow the amputee to develop many new behavior patterns, as previously discussed. It has been shown that the full range of sensory cues that will become available to the amputee is not present even after two years following amputation. By this time the amputee has developed new patterns of performance and usually is extremely reluctant to undergo an extensive training program, regardless of the benefits that might accrue.

Finally, despite the need for improvement in prosthetic devices, there is a more immediate problem of getting the amputees to utilize more fully the prosthetic devices presently available.

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THE ROLE OF THE ENGINEER IN PROSTHETIC DEVELOPMENT

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The engineer is making ever-increasing contributions to the general field of medicine. New techniques conceived for the solution of special physical problems are finding application in certain medical situations. The electron microscope, which has helped to extend our knowledge of the physical properties of matter, also has made it possible to examine the nature of the virus. The discovery of atomic fission has made possible a selection of radioactive isotopes useful in a variety of medical applications. Many other similar instances might be cited.

In my opinion, however, it is in the field of orthopedics that the greatest community of interest between the engineering and medical professions exists. The orthopedist thinks of the human body in terms of structure and function, just as an engineer thinks of a complicated electromechanical device. When the orthopedic surgeon performs an amputation he realizes that the most successful rehabilitation can occur only if he permits his patient the greatest amount of residual function consistent with the removal of the cause for surgery. When the design engineer contemplates a prosthetic replacement, he must consider the amount of residual function available to the amputee, and the activity that must be replaced.

In a design situation, the engineer must be presented with a set of specifications. He then endeavors to adapt the techniques he has learned and materials and processes that are available to the solution of the design problem.

In the design of prosthetic devices the engineer must consider four major factors: (1) function, (2) response to some control from the amputee, (3) sensory feed-back to the amputee, and (4) satisfaction of the amputee's emotional needs. In addition to these four major, special requirements, the device should meet such normal requirements as an adequate service life and satisfactory weight characteristics. It should be fabricated with materials available to all prosthetists, and should be designed in such a way that it can be manufactured by techniques and processes generally available and generally known.

To satisfy these requirements is no easy task. At the conference on which this monograph is based, Charles Bechtol suggested that "perhaps the most basic principle in the problem of prosthetic replacement is the fact that the human mind thinks only in terms of movement and not in terms of individual muscle action. Translated into terms of control of the prosthesis, this then means that the control of a single motion of the prosthesis such as the opening or closing of an artificial hand must be controlled by a single motion supplied by some part of the patient's remaining anatomy."

Any review of our present success in satisfying the major design requirements would reveal the following facts.

We are making progress in providing more than rudimentary function to

upper-extremity amputees. Obviously it is impossible to reproduce the delicate balance of the dozens of muscles that go into any simple function of the intact human hand. For the present, then, we must analyze the function of the extremities and, in attempting to design a successful prosthesis, duplicate only the most important functions and keep the control systems at the simplest possible effective level.

We are accomplishing this in present-day upper-extremity prostheses, making it possible, by movements of the shoulder or the body, or both, to control grasp, rotate the hand, or flex the elbow. Where several movements are required, all of them may not be done concurrently, but certainly they can be done sequentially—even if in certain situations some movement must be locked before another can be performed.

There is hope that eventually we may be able to more nearly approach the delicate balance of the dozens of muscles. The progress being made in the field of electronics, in the miniaturization of equipment, in printed circuitry, and in programmed sequences in a system holds out promise that, in the near or not too distant future, we may develop electronically controlled, electrically actuated upper-extremity prostheses that will provide much more sophisticated function than that available from the present devices.

The means for controlling these, however, are not yet available to the engineer. Considerable research is necessary to determine what muscle groups combine to perform any single activity and where we may "pick off" the signals that trigger these muscle groups. When we have more knowledge of these phenomena, we may be able to coordinate it with our other skills and provide a system that will respond to the will of the amputee substantially as it does to that of the intact man.

We have made little progress in improving lower-extremity prostheses, except perhaps in providing more adequately functions that have always been available in such devices. There have been improvements in the fitting procedures. In most cases cumbersome attachments have been eliminated. Better components, knees, and feet are being provided. Controls to the swing phase of locomotion that more nearly simulate the natural pattern have been developed. All this has improved level walking for the lower-extremity amputee. Nonetheless, we cannot yet suggest an energy source or a control and transmission system that would permit the amputee to walk up and down stairs and ramps. When new and more compactly packaged energy sources that provide the necessary power requirements are discovered, we may then provide the lower-extremity amputee with maximum function.

We have not yet been too successful in providing sensory feedback. Means must be developed to provide tactile recognition and position location and to convey these elements to the individual through appropriate sensory channels. Only then will it be possible for the amputee to position a prosthesis in the manner in which the nonamputee places his natural extremities, without recourse to visual cues.

The engineer must conduct his work fully cognizant of the emotional life of the amputee. He should constantly confer with the psychological scientist to assure that functional improvements do not impose emotional conflicts.

Much evidence confirms the fact that the newer materials that result in improved color and texture are more acceptable to the amputee. The continued reduction of noises associated with a prosthesis also results in his greater satisfaction.

The improvements in a prosthesis should not be made entirely without consideration of cost, of ease of maintenance or repair, or of possible replacement. The engineer, therefore, should be constantly in contact with the prosthetic industry to make it aware of the conditions that are to be met in satisfactorily fabricating a new device.

Further research is desirable and necessary. We must know more about locomotion, particularly pathological locomotion. We must know more about the component parts that produce a complex activity. We must find synthetic materials compatible with human tissue, that is, substances with properties somewhat similar to those of human bone and tendon and muscle. These may make it possible to attach the structural part of a prosthesis directly to the bone and control it directly by the residual muscles or tendons.

Better prostheses are needed. Certainly if they are to be achieved, it can be only through a continuing cooperation between those disciplines represented here: the biological and psychological, which understand man, and the engineering or physical sciences, which can deal with the materials and mechanisms. Together they may eventually provide the amputee with maximum function.

Part II. Interdisciplinary Research

PROBLEMS IN INTERDISCIPLINARY COORDINATION AND COMMUNICATION

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It is my purpose to point up some of the problems encountered in effecting satisfactory communications among various professional disciplines that are concerned or should be concerned with a given research problem, and to coordinate their individual efforts so that a total or comprehensive approach may be achieved. My concern with the subject of human disabilities and rehabilitation has been from the viewpoint of an internist and public health administrator, but I feel certain that the principles encountered in coordination and communication are applicable to those found in studies in the basic sciences and related fields.

I should like to cite, as an example of a satisfactory system of communication and coordination, the organizational structure of the Interdepartmental Health Resources Board of the State of New York. This board, organized in 1956 by an act of the State Legislature, was designed to permit and to stimulate joint planning, demonstration, and research in health areas in which two or more state departments or agencies have major concern. It is made up of the Commissioners of Health, Mental Hygiene, Education, Social Welfare, Correction, and Labor, and the heads of the Workmen's Compensation Board, the Division of Parole, and the Joint Hospital Survey and Planning Commission. At the working level it is primarily interdisciplinary, as each project taken up by the Board is explored by a committee consisting of members appointed by the various departments concerned, but representing particular disciplines.

Some of the major problems faced by the Board in interdisciplinary research in eight general categories lie as follows: (1) lack of knowledge of the basic nature of other disciplines and what they have to offer to the area of study in which one is engaged; (2) lack of an effective mechanism for communication between disciplines in a given research project; (3) confidentiality of information; (4) lack of utilization of all disciplines concerned in initial planning; (5) lack of an adequate medium of exchange of information among disciplines in regard to current activities and research; (6) lack of coordination of interests and efforts; (7) improper allocation or channeling of funds; and (8) personal and interpersonal problems.

Lack of knowledge of other disciplines. We may aptly apply the statement, attributed to Josh Billings, that "taint so much what we don't know that hurts us, it's what we know that ain't so." Working in one discipline, we may be ready to admit that we know little or nothing of the basic nature of another discipline or how the latter might contribute to or enhance our own efforts. More serious is the situation in which we believe we are quite

familiar with the nature of other disciplines while, in truth, our information is either erroneous or entirely superficial. In the latter instance, once the veneer is off, we find ourselves in complete ignorance.

The Resources Board is concerned with such health areas as medical care for the aging, rehabilitation, mental retardation, emotionally disturbed children, and chronic alcoholism. As I stated above, for each of these problems we have committees composed of departmental appointees representing various disciplines. For example, our Committee on Mental Retardation includes the disciplines of medicine, including public health administration, psychiatry, pediatrics, and internal medicine; education, including psychology; child welfare; and vocational rehabilitation. This committee is responsible for planning, developing and, subsequently, supervising research studies that will yield new information and assist the state in its long-term program development for the mentally retarded. Our experiences with this committee duplicate those of each of our other committees. The individual members are recognized as authorities in their chosen fields and have had direct experiences with the problems at hand. Initially, each member was under the impression that he had a fair knowledge of the nature of the professional fields represented by his co-members. Discussions quickly revealed that such knowledge was negligible, superficial, or erroneous, and that it was necessary to devote much time to general orientation before the basic problems of the committee could be undertaken. Individual members have found these initial orientation sessions most helpful, not only from the viewpoint of the committee's projects, but for assisting them in their own areas of responsibility.

Lack of communication. This, of course, occurs readily within a discipline, but is more rampant between disciplines. If I may turn again to the field of mental retardation, we have established three demonstration clinics for the evaluation of mental retardates. It is the purpose of these clinics not only to provide service to the community but to explore methods by which we might obtain a better understanding of the problems of mental retardation and thus make more adequate plans to meet these needs. Each clinic has a full range of the disciplines considered to be concerned with mental retardation, and there is no problem of an interdisciplinary approach within the clinic. The problem occurs when the assistance of professional groups outside the clinic is required to help in the evaluation of a mentally retarded child in regard to his previous progress and evaluations. If the total picture of the mentally retarded person is desired, it is necessary to establish adequate communication channels with the educators and psychologists of the school system, with the case workers of the family agency that may handle the social aspects of the case and, in the instance of the older retardate, with the vocational rehabilitation counselors who may have much information regarding their client in respect to his vocational potentials and training abilities. Despite the development of information-request forms and group meetings to explain the purposes of the project, the procurement of necessary information often bogs down.

Confidentiality of information. This proved a troublesome problem to us when we were engaged in a survey of the prevalence and needs of physically handicapped persons in a rural area of the state. Obviously the information available in the files of the private attending physician, including the history and findings at the onset of the disability, the course to date, and the attitude of the patient, were most vital to the study. Although there are ways of circumventing this situation, the problem of confidentiality of records may prove quite troublesome in clinical research.

Lack of utilization of all disciplines concerned in initial planning. Probably the most common example of this aspect is the failure to bring in a qualified statistician during the very first phases. The same thing might be said of late consultations with such disciplines as social science and cultural anthropology. Too often the representatives of these fields, from whom we have asked assistance, find that we have not collected sufficient information to permit them to give us the kind of consultation we seek.

At the present time the Board has had to contend with a project that took fifteen months to complete and six more months to record. It cost about \$45,000, involved almost 1000 subjects, and called for considerable cooperation on the part of innumerable public and private agencies throughout the state. The study was a good one, and its findings will undoubtedly be of considerable help to us in long-term planning for mentally ill children. However, many of the findings are not as clear-cut as they might have been had adequate statistical planning and guidance been available from the beginning, in spite of the fact that statistical consultation had been purchased on an hourly basis from an outstanding university. This is not the same thing as having one statistician stay with a project from the beginning. The basic flaw in this project concerned the initial sample which, of course, is uncorrectable at this late stage. The board has just employed an associate biostatistician who will work with projects in which we are interested. He is now working with the psychiatrist, social workers, and other persons involved in this problem project to be certain that the findings, although necessarily limited because of the sampling, will be foolproof.

Lack of an adequate medium of exchange of information. The professional journals, national, regional, and state meetings, plus special publications on current research projects within a discipline, provide means of learning what our colleagues are doing. The problem is more significant where the disciplinary lines are crossed, however, because, although we may have access to publications of other disciplines, there is far too much reading matter within our own fields to permit contemplation of even an extension of the material. Fortunately, several journals do a fine job of extracting articles from all disciplines concerned with their subject.

I believe one of the best examples of this is in the field of alcoholism, where the *Quarterly Journal of Studies of Alcohol* abstracts articles from all disciplines concerned with the subject. In addition, this publication has prepared an abstract archive of alcoholism literature, of which it produces about eleven duplicates. These archives, classified for more convenient use, have been

made available to various agencies that may then serve the professional groups in their communities. Additions are made yearly. Our board possessed one of these duplicate archives, but we have recently transferred this to the State of New York Medical Library, Albany, so that its services may be made more widely available.

Lack of coordination of interests and efforts. By this phrase I refer to the general activities of the various disciplines rather than to the undertaking of a specific problem. Too often our professional research groups go off in their own directions instead of coordinating their efforts toward a specific target and a more meaningful whole. Obviously this is related to several of the problems already discussed, such as lack of communication and lack of knowledge, and it may be more difficult to overcome because it is not directly related to a specific problem. In this connection I should like to quote from a recent editorial in *Geriatrics*,¹ which deals with gerontology and the university's opportunity and challenge: "None of us can escape the personal experience of aging. Our unsolved problems, moreover, affect groups as well as individuals. These unanswered questions impinge on medicine, education, industry, government, and virtually every other facet of society.

"Thus gerontology offers comparable challenge and opportunity to the medical school and the liberal arts college, to biologist, psychologist, and sociologist. Because it is inter-disciplinary in its make-up, gerontology holds ever-reinforced interest for the university administrator, whose first responsibility is the advancement of the professional efforts of his entire faculty. The administration of a progressive university should be alert to the importance of gerontology because of other potential benefits to faculty, student body, and even to financial position.

"University research, by its inherent nature, is often isolating. Because of this isolation, the successful investigator sometimes loses touch with the changing times and even with colleagues in neighboring fields.

"Broad and forward-looking study of inter-disciplinary questions, such as those existing in the field of gerontology, can often enlarge academic perspective. Professors who work together productively share a rewarding experience. When they scrutinize human adjustments now being made in society at large, they further dissipate the research preoccupations that sometimes interpose between themselves and others. Ultimately the student body benefits from both kinds of enriching activity on the part of the faculty."

I am certain that the university is well suited to overcome this problem of lack of coordination among disciplines interested in a common field, but I am equally certain that the same goal can be achieved in other areas, as among community agencies, among governmental agencies, and in industry, where the effort will be made.

Improper allocation or channeling of funds. Research on any basis requires adequate funds. This point requires no elaboration. One potential problem that arises from the earmarking of public or private funds for a particular purpose or agency may be a restriction of the utilization of those funds for an interdisciplinary approach. For example, funds given to a clinical department may be so specifically earmarked as to block allocations to certain

investigations in basic research that should necessarily precede or at least run parallel to clinical investigations. I believe such difficulties can be handled most satisfactorily through subcontracts. However, the common occurrence of pressure groups, led by persons with vested interests who have been influential in procuring the funds may, because of their demand for a quick answer to a limited field, obstruct such an interdisciplinary approach.

Personal and interpersonal problems. Actually I should give this category a very high priority because, where cooperation or coordination is concerned, human factors may well outweigh organizational factors. What can we do about the generally uncooperative person in the field of research? We certainly see sufficient examples of this on an intradisciplinary basis. It is more evident on an interdisciplinary basis. To what extent is such isolation due to personal or vested interests, with concern over sharing of credits, or to misguided loyalty to the agency by which the worker is employed or the professional group to which he belongs? Possibly to some degree it is attributable to a certain conservatism in regard to what other groups can contribute. This sometimes blends indistinguishably with plain stubbornness or with an attitude of "I don't know what they represent, but I'm against them." I shall not hazard a guess as to how common the personal and interpersonal factors are, and I am certainly not suggesting that a significant number of research workers should see a psychiatrist. I believe we may safely say that, in general, those entering the research field are men or women who search for the truth with an open mind and with little thought of personal gain. Unfortunately, no breed is pure, and that is why we must contend with this last problem.

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INTERDISCIPLINARY RESEARCH IN REHABILITATION

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For almost a century many public and voluntary programs have been established to contribute to the well-being of disabled persons of all ages. These programs have utilized the services of several professions and technicians, as well as lay people, in the provision of services to such patients. Although the earlier years were characterized by scattered and unorganized professional effort, considerable progress in meeting the needs of disabled persons has been made. In addition, a small body of technical information has appeared.

Particularly since World War II, these independent professional contributions have begun to emerge into a more orderly and organized effort which, in the absence of a more appropriate term, we refer to as rehabilitation. Generally speaking, this term reflects a coordinated approach of clinical practice in meeting the varied needs of disabled persons.

In any discussion of research on rehabilitation one immediately faces the problem of definition. Efforts to define this umbrella term have not met with universal agreement or acceptance, although many man-hours have been invested in the process. Like "mental health," there is hardly a term in the vocabulary of physicians and behavioral scientists that is as elusive and ambiguous as rehabilitation. It continues to mean many things to many people. Many people use it without attempting to specify the idiosyncratic meaning the term has for them. Naturally this complicates things for those who wish to promote and improve rehabilitation and for those who wish to initiate concern with systematic rehabilitation theory and research.

At the same time, I must point out that few efforts have been made to define rehabilitation research or to delineate its boundaries. We do know that contributions in one field open up new opportunities for improved services to disabled persons in other fields. For example, advances in drug therapy to control epileptic seizures make it possible for the rehabilitation counselor to place the individual in a wider variety of occupations. At the same time it might reduce, for the individual, some of the undesirable psychological components in the adjustment to disability.

The absence of precise, standardized definitions does not appear to me to constitute a serious obstacle in introducing a scientific approach toward investigating the problems of human disability, however. Definitions are primarily a matter of convenience. A definition in itself solves no problems nor does it add to knowledge. Its major usefulness rests primarily in achieving the purposes of science, and the absence of a precise definition should in no way deter our efforts to progress through research. In fact, we must look to research to bring some semblance of order out of the present confusion.

I am more concerned, however, with our state of knowledge about adjust-

ment to disability. One group of investigators¹ has expressed it rather forcefully: "The state of our knowledge of these matters [adjustment to physical handicap] is little above the level of folklore in many respects, and in others, that which is known has very limited circulation. Yet, this limited knowledge serves as the basis for such important practical affairs as doctor-patient relations, occupational therapy regimes, hospital organization, industrial employment programs, industrial accident legislation, vocational rehabilitation programs and benefits for disabled veterans. This is a field ripe for investigation; techniques are available for the solution of problems of great theoretical and immediate practical importance." The last sentence is encouraging, and now that a Federal Rehabilitation Research Grant Program is available, the future looks more promising and hopeful.

In spite of the status of our knowledge of adjustment to disability, certain basic principles have emerged that have implications for research. One principle that has emerged from rehabilitation practice, accepted by practitioners and described by Whitehouse,² is that in the rehabilitation of disabled individuals there is but one method, one procedure, and one purpose. The method is the whole-person approach; the purpose, the satisfaction of every important need of the handicapped person; the procedure, one that encompasses the organismic treatment of the individual as opposed to handicap as a specific entity. Human disability is now viewed as an ecological concept—the interaction of environmental and internal forces and stresses, both physical and psychological. Treatment must therefore be dynamic and fluid in order to keep pace with the changing person, and must consider all of the individual's needs. In this context, rehabilitation must be looked upon as a continuing process, from the initial to the terminal contact with the patient and his family.

Naturally, no single profession, particularly during the current era of specialization, can be expected to meet the entire range of each individual's needs. What has emerged is a recognition that rehabilitation requires the marriage of professions, or team approach. In other words, the collaboration of professions is a fundamental requisite of providing disabled people with rehabilitation services.

Since rehabilitation involves services to people by public and voluntary groups, including lay participation, rehabilitation research is in a position similar to that of mental health, and much of the work in the immediate future will be directed toward improving the scientific basis for program services and evaluating the effects of practical operations.

Evaluation of rehabilitation activities is necessarily difficult. It must cope with the influences of numerous variables, both within and outside the individual, must recognize the participation and contribution of several professions, consider the validity of those basic assumptions upon which human behavior relies at the present time, and take into account the personal beliefs and attitudes of both the evaluators and those whose activities are being evaluated. Any assessment of practices must consider the possibility that more vigorous evaluation might alter impressions of achievements and might reveal that, in some instances, operations that have led to positive results

have been predicated upon basic assumptions that have either been wrong or of secondary importance. Other basic assumptions may be proved correct or be susceptible to proof.

Although I believe much of our research will be directed to evaluation of practical operations, I do not mean to imply that theory development will remain ignored. Theory development, upon which progress depends, will continue, but perhaps not with the same degree of emphasis as the former. It may, to some extent, have to wait upon further progress in evaluation.

Since rehabilitation practice by its inherent nature requires the collaboration of professions, and since major research emphasis for some time will be directed toward the evaluation of program operations, any approach toward investigating problems of human disability must be interdisciplinary.

Recognition of this approach is by no means limited to human disability. Permit me to turn briefly to the field of research in general. The literature, particularly in the social sciences, is filled with discussions of interdisciplinary research, its values and limitations. Social and psychological scientists have come to recognize that the phenomena they observe cannot be encompassed by the narrow boundaries of any particular discipline. Recognition includes the often reiterated viewpoint that the individual and the group do not represent a dichotomy but, instead, a single field of interaction. The acceptance of this viewpoint has led to an enthusiastic, widespread trend toward "interdisciplinary collaboration," whereby a combination of social scientists, physicians, and psychiatrists attempts to study human behavior in the interactive situation. While there are no comprehensive statistical data on the development of organized interdisciplinary research, independent reports by the Russell Sage Foundation,³ the Brookings Institute,⁴ and the Social Science Research Council⁵ cite the development as one of the most scientific changes in the social sciences over the past twenty years.

Strictly speaking, interdisciplinary cooperation means a reciprocal interchange of ideas and data between two or more specialists. Obviously this type of collaboration is possible in many forms, ranging from the relatively intimate self-regulated cooperation between two specialists, proceeding in an intimate and friendly spirit, to elaborately organized platoons of specialists supervised by complex administrative machinery. It is equally possible, of course, that the extent of the collaboration between the participants may be limited to narrow exchanges of ideas and data.

In my enthusiasm to encourage interdisciplinary research I do not imply that this approach is free of limitations. The pitfalls, such as communication, differences in research orientation, a common denominator of knowledge, and status position are well known. In rehabilitation we have an additional problem. The findings and discussions of the many professions are disbursed among a wide variety of professional publications. No serious effort has been made to bring this literature together to provide a basic body of knowledge or to determine what significance the findings in one profession may have for another profession.

The kind of interdisciplinary enterprise that appears to me as fundamental to the study of human disability or rehabilitation involves more than two

collaborators, at least two disciplines, and a commitment by those engaged to work together to proceed collectively in their research rather than separately. This requirement may appear elementary to most readers of this publication; nevertheless, to one who has personally reviewed several hundred applications for rehabilitation research grants, it has not yet become a reality. This includes applications from some of our better institutions of higher learning. The practice of interdisciplinary collaboration has not yet permeated the conceptual thinking of researchers to the same extent it has that of the clinical practitioners.

However, the concept is beginning to emerge, and I should like to cite two examples that reflect increased recognition of its requirement in investigating the problems of human disability. As a means of accelerating the identification of rehabilitation research needs, we have made grants to several institutions to identify these needs in several different professional fields. One institution prepared a statement on the research needs in the physical rehabilitation aspects of vocational rehabilitation.* The authors classified their inventory of research needs into four broad categories: (1) basic physiological studies, (2) new and improved prognostic techniques, (3) dynamics of individual and group motivation, and (4) quantitative evaluation of functional capacities. Particularly significant to me was the inclusion of motivation as one of the major areas of research needs in physical rehabilitation.

A second example is the Prosthetics Research Board of the National Academy of Science, National Research Council, Washington, D. C. I happened to serve as the then Federal Security Agency liaison representative to the committee in its formative period. When little was known about prosthetics, there was much confusion in determining where to start in developing a research program. I recall that someone suggested to the engineers and physicians the possibility of turning to the civilian amputees themselves for an inventory of some of the problems experienced in the wearing of prostheses. At this time, recognition of the individual, his attitude, feelings, and reaction to his disability and prostheses was, in effect, heresy. It was assumed that the problems of prosthetics could be solved by the engineer and the physician.

Fortunately, our understanding has now matured to the point of an awareness that the basic unit of study is a biomechanic entity made up of the amputee and his prosthesis. As a result, new research horizons have opened up in the prosthetic field that are no longer the exclusive province of one discipline, but the meeting ground of a number of professions.

Finally, and still on the positive side, investigators can tackle problems of greater dimensions through collaborative effort than they can individually. Such effort provides a broader outlook, stimulates more people, and may yield more adequate interpretations and findings. When one point of view is pitted against another, something is likely to emerge beyond what each individual contributed. Individual contacts and consultations can rarely accomplish the interaction experienced in an effectively functioning inter-

* Prepared by the Faculty and Staff, Department of Physical Medicine and Rehabilitation, New York University-Bellevue Medical Center, New York, N. Y.

disciplinary group. If interdisciplinary research is undertaken when the nature of the problem demands it, it should make increasingly valuable contributions to understanding and solving some of the important problems associated with human disability.

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METHODS AND SOURCES OF STIMULATING INTERDISCIPLINARY RESEARCH

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The Public Health Service is the federal agency charged by law with the responsibility for conducting and supporting research into the causes, diagnosis, prevention, and treatment of diseases and disabilities of man. Certainly in this mission there is need for a wide variety of disciplinary approaches which, to be effective, must be welded together into a whole program. To accomplish this end, interdisciplinary research is essential, since completely independent research in the individual disciplines produces only fragments of the needed answers and since these fragments must be assembled in order to produce the whole. Without advance planning the end result may resemble the amateur clock repairman's handiwork—many parts left over and a unit that will not function. Modern assembly line manufacture depends upon the planning that assures availability of the parts in the right place and at the right time, and represents the interdependence of special and essential skills and services. Modern scientific research is closely analogous, and both manufacture and research depend upon individual effort and skill to improve the quality and function of the integral parts.

The Public Health Service has chosen to carry out its mission in two ways: by direct research in its own laboratories and field stations and by grants of funds to nonfederal research institutions whose research scientists have submitted satisfactory proposals for the conduct of needful and promising investigations. In its direct effort there is careful planning to ensure that the disciplinary approaches complement each other. As a result, in ever increasing degree, these disciplines are found working together rather than independently. One notable example is the work at the National Institutes of Health Clinical Center. This same pooling of disciplinary competence toward a common objective is increasing also among the Public Health Service grantees. In both instances the end product is often not only more quickly produced and of better quality, but also it is apt to be nearer to application or utilization in the accomplishment of our mission.

It is of interest to recall the situation that led to the extramural or grants program of the Public Health Service, particularly since it was established initially in behalf of interdisciplinary research. During World War II the famous Manhattan project in nuclear research had a contemporary and more loosely organized counterpart in the biological sciences under the auspices of the Office of Scientific Research and Development. At the close of active hostilities in 1945 there were approximately fifty research projects of biological or medical interest under way by multidisciplinary teams of investigators. These projects became the nucleus of the present cross-the-board research grants program of the Public Health Service. Funds appropriated for these

projects plus funds from additional sources made a total of \$780,000 available for the Public Health research grants program in its first year, 1946. By 1958, the direct appropriation for this purpose had grown to \$101,265,000. As the program gained in financial support it became possible to include larger components of basic research, much of which is also conducted by the multidisciplinary approach. The team approach not only concentrates effort on a particular problem, but often uncovers the need for further research, and it stimulates the development of new techniques and equipment. Modern pharmacology, for example, has become an adventure in electronics.

Preliminary to a discussion of governmental methods and sources of stimulating interdisciplinary research, it will be helpful to point out some of the commonly recognized problems involved. In the field of the life sciences, as in other fields, the interdisciplinary approach is not a simple one, and the degree of difficulty is directly proportionate to the scientific proximity of the disciplines. Such overlapping disciplines as physiology, biochemistry, and pharmacology do not present a particularly difficult problem. When disciplines are further apart, as, for example, psychology and automotive engineering, the problem of cooperative research in two or more such fields is one of increasing difficulty. The 11 million highway traffic accidents in 1957, with 40,000 deaths, provide dramatic indication of a problem that requires an interdisciplinary approach involving, in addition to the foregoing, such disciplines as physiology, toxicology, medicine, highway construction, and traffic management, to mention only a few. However, the existing research projects directed toward reducing this enormous public health and financial loss are very few in number, and they are lagging far behind technological advances that may not be the direct cause of them, but at least make accidents increasingly possible.

In spite of the growing need of the interdisciplinary approach to the increasingly complicated research problems concerned with health, there are relatively few investigators who are competently trained for such effort. Superimposed on this shortage is a reluctance of investigators to go into such research, and for good reason. As a result of his heresy, an investigator's scientific papers are likely to be of less interest to the journal or journals of his primary discipline, or may even be returned as of insufficient interest to their audiences. His papers presented in scientific meetings may seem out of place when presented before his former colleagues. In short, he may suffer a serious penalty for the change in the direction of his scientific efforts. No man wants to incur such a forfeit unless his dedication to the new interest is overwhelming.

Furthermore, as our total knowledge increases, the relative area in which any one individual can specialize becomes smaller and more restricted. The research scientist is usually immersed in his own limited field and jealous of his independence to pursue the problems of his own choice in his own way. This is, indeed, essential to his personal development and productivity. To relinquish this autonomy in order to fit into the pattern or plan necessary for the successful accomplishment of interdisciplinary research requires self-

sacrifice, a breadth of view, and a dedication to the general problem not often found. The success of the interdisciplinary approach is dependent upon the over-all plan or design which, in turn, is dependent upon the excellence of the component parts contributed by the individual scientist in his own specialty. Thus we have a dilemma. The solution is not the creation of generalists to displace specialists, but the recognition of the interdependence of disciplines and the willingness to invite expert participation from other fields. There must be a continued effort to maintain and increase the individual's sharp focus upon the details of his primary discipline, coupled with an increased effort to provide him with an awareness of the potential contributions of other disciplines to the solutions he seeks. The ability of the individual will determine the limits to which such awareness can be developed.

The previously mentioned difficulties in recruiting scientific manpower into interdisciplinary research are compounded by the general shortage of research manpower and the wide separation of the disciplines in which competence may be required. The shortage of research manpower has for some time given increasing concern to those who have foreseen its consequences. For some years men of vision in Congress have been working with leaders of scientific thought to bring about an increase in research manpower in the biological sciences having to do with health. This effort has been reflected in the annually increasing appropriations for this purpose.

There is still another cause of the manpower shortage peculiar to interdisciplinary research. There is no way to train Ph.D.s or M.D.s for interdisciplinary research if the disciplines likely to be involved are not known during the individuals' period of graduate training. The M.D. has been introduced to biochemistry, pathology, virology, epidemiology, and other disciplines, but he is fortunate if his medical training has involved any research in even one of these.

There is no way to overcome the difficulty that attaches to wide separation of fields except as the interdisciplinary approach to research grows sufficiently in importance for its needs and opportunities to come to the attention of students entering graduate training. It may well be that the interdisciplinary area of psychopharmacology, for example, in which the effects of tranquilizer drugs are insistently demanding more attention, may soon have sufficient importance in the eyes of predoctoral students to persuade them to major in psychology or psychiatry, for example, and minor in pharmacology. Continued and insistent publicity, at any rate, is a well-known factor in arousing scientific and general public interest in any interdisciplinary area and in assuring an ample supply of research funds.

It should be emphasized, however, that preservation of the scientist's freedom of choice, uncoerced by the interests of others, particularly of those wielding economic power, is essential to the preservation of research itself.

In the foregoing we have considered the general shortage of research manpower and the problems of acquiring familiarity in a secondary field. Let us now consider some of the things that are being done to increase both manpower and an interdependence of disciplinary interests.

The need for multidisciplinary interests has been recognized for many

years: ever since we began developing choices of curriculum for graduate students. There is now a general trend in many institutions to encourage students to choose first and second minors in disciplines more widely separated from the major discipline and from each other than in the past, yet in disciplines of common interest to specific fields or research areas. There is also an increasing tendency to broaden the terms used in designating areas of research and interest so that such areas are thought of as disciplines. Epidemiology, which I mentioned before as a discipline, is a good example and one of long standing. It incorporates many basic and normally widely divergent disciplines in its approach to research. In fact, the particular combination of disciplines involved is found to vary with the specific epidemiological need. The relatively new field of epidemiology of chronic disease is still undergoing development to determine the specific basic disciplines it requires. Environmental health, now achieving a similar disciplinary or superdisciplinary status, constitutes a research field made most difficult because we are experiencing the most rapid environmental changes in the history of mankind. Still another such amalgamation of basic disciplines is under way in the field of physical biology, although the experts are still arguing as to whether the physicist should be familiarized with biology, or vice versa. The order of preferred precedence may be established in a statistical sense, but it is hoped that it will not preclude an approach tailored to the individual's ability.

The federal agencies concerned with this problem, particularly those of the Public Health Service, have initiated coordinated programs of fellowships and training grants to enhance the research training of investigators. The funds expended annually in this effort since 1946 have been increased roughly in proportion to the increases in research grants. It should be pointed out, however, that only a part of these funds is expended in direct training for interdisciplinary research; the funds are used chiefly for the support of training and training opportunities in specific disciplinary areas so fundamental to both the disciplinary and interdisciplinary approaches.

Another Public Health Service program, designed to assist the medical schools in studying and remedying their curriculum requirement in order to discover and encourage research interests, is the Experimental Training Grant Program initiated in the fall of 1957. Many more schools were desirous of making studies in curriculum programs than the limited funds could support, and it was planned to make further funds available during 1958. This interest has been reflected, of course, in many efforts financed by the schools themselves with nonfederal support. Notable among these are the so-called "vertical teaching" plans inaugurated at the Western Reserve Medical School, Cleveland, Ohio, and at the University of Texas Dental Branch, Houston, Texas, both of which bring several disciplines to a common focus upon a specific problem. No single one of these efforts to increase trained manpower, either federal or nonfederal, can be relaxed; rather, they must be intensified to meet the problems ahead.

In spite of the shortages in manpower, facilities, and finances to conduct both disciplinary and interdisciplinary research, there are many outstanding

examples of success in both. Since we are concerned here with interdisciplinary research, the following are noteworthy: significant advances in the chemotherapy of malaria and tuberculosis; development of penicillin production and its use in the control of venereal disease and streptococcal infections; and the subsequent development of a large armamentarium of other antimicrobial agents against a wide variety of diseases and parasitic infections.

Perhaps the most ambitious voluntary effort in interdisciplinary research yet attempted is the search for chemicals to control cancer. In this effort the team includes organic chemists, biochemists, endocrinologists, pharmacologists, geneticists, statisticians, pathologists, tissue culture experts, veterinarians, microbiologists, and various types of clinicians. Groups in various parts of the country are contributing their efforts and skills to the whole, each discipline contributing what it can do best and on an equal basis. The investigations may be initiated individually or as cooperative programs found mutually acceptable. The groups and individuals involved have been organized in a national effort under the leadership of the Cancer Chemotherapy National Committee. This group is the top policy-making committee of the Cancer Chemotherapy National Service Center, which is part of the National Cancer Institute at Bethesda. The committee in itself represents a cooperating group of voluntary organizations, industry, and government agencies. Each of these groups is contributing either in funds, personnel, materials, or knowledge. The greater part of the funds is provided through congressional appropriations to the National Cancer Institute. The Public Health Service provides a focus for the program activities through the Cancer Chemotherapy Service Center of the National Cancer Institute. This common effort has brought together many scientists of diverse disciplines who are now learning to work together toward a common goal.

The application of a similar approach to the problem of aging and the aged is under way and, although the problem is highly complex and to a large degree involves disciplines in the social and behavioral sciences, progress is confidently expected.

Multidisciplinary research supported by both federal and nonfederal agencies is continuing on a smaller scale in almost every research center in the country. The Sloan-Kettering Institute is one such notable center.

"Nothing succeeds like success." It is human to like to be a member of a winning team, and there is satisfaction in having a part, even a small one, in the solution of a major medical problem. If the problem is great and the interdisciplinary approach to it seems promising, I think we shall find not only the specialists necessary to work together for its solution, but also the federal and other funds for their support.

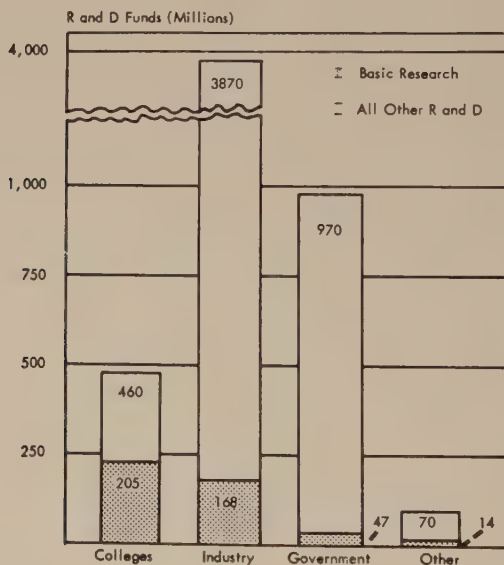
PROBLEMS IN SUPERVISION AND FUTURE PROSPECTS OF INTERDISCIPLINARY RESEARCH

By Harold K. Work

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In the past fifty years the research pattern of the country has undergone marked changes. At the beginning of this period research was concentrated largely in the hands of the universities. Today the universities are running a poor third to industry and government in the total amount of research done. In basic or pioneering research, however, the universities still lead (FIGURE 1).

Sources of Research



From Chemical and Engineering News, page 18, July 29, 1957.

FIGURE 1. Distribution of research.

It is natural, therefore, that universities should be leaders in interdisciplinary research.

This is true even though there are certain influences in the university that work against interdisciplinary cooperation. A few years ago I was asked to speak at a dinner at Columbia University, New York, N. Y., about research. The toastmaster was D. B. Hertz. In talking about interdisciplinary research, I quoted from his book. *The Theory and Practice of Industrial Research* (1950), as follows:

"As Keys and Brozek point out, successful execution of cooperative research requires modification of the competitive work habits which have been fostered by the hyper-individualistic philosophy of life expressed in the traditions of university research (and) . . . a second barrier to interdepartmental cooperation is seen by Dr. May in the positional system within each department; the young scientist has a greater chance of advancement if he saws wood on his own wood pile, follows the traditional paths and works for the greater glory of his department and does not participate in interdepartmental, collaborative projects. The third barrier is formed by a set of traditional attitudes and ideas such as the belief that scientific discoveries are always the products of

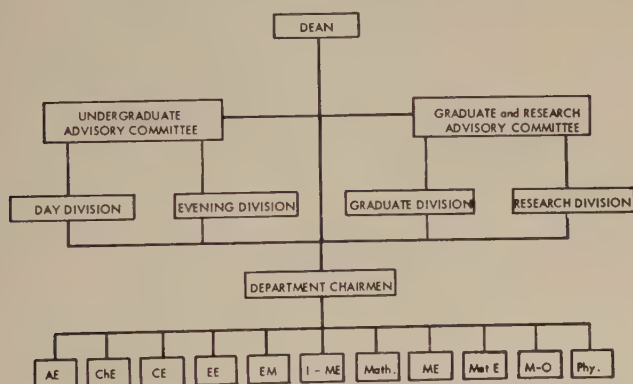


FIGURE 2. New York University College of Engineering simplified organization chart, September 1957.

individual minds, or that the cooperative setting limits the freedom of the scientists to follow the dictates of his own intellectual curiosity. The fourth barrier is a result of university training in individualistic work habits." When I finished speaking, Hertz remarked that he had written this part of his book before he was associated with a university; if he were redoing the book this section would be made much stronger.

There is no question that the universities, by cherishing freedom of individual thought and speech and then protecting it with tenure, do not promote cooperation. Hence I propose to discuss the methods by which we have approached the problem of interdisciplinary research in the Research Division of the College of Engineering at New York University. But first let me describe how our research is organized.

The sponsored research of the College of Engineering is integrated with the academic activities, rather than being set up as a separate experiment station or foundation (FIGURE 2). Here it will be noted that the college is divided into four administrative divisions; day, evening, graduate, and research. The two undergraduate divisions have an advisory committee, and the graduate and research divisions have an advisory committee. These committees are designed to coordinate the activities of the divisions having common interests. The research itself is carried on for the most part in the academic

departments. The research activities of the college are quite extensive and, according to the Engineering College Research Council directory, we have the fourth largest program among the engineering schools of the United States. Annual expenditures exceed three million dollars per year, and approximately 500 people are involved in carrying out the work on 150 projects.

Integrated research of the type described above has much to commend it. The academic contribution to the activity consists of a group of brilliant scientific minds, housing, equipment, and a framework of organization and service facilities. The sponsored research helps bring in equipment and funds to make the efforts of these scientists much more effective. Each helps the other, therefore, in synergistic fashion. That is how integrated research looks on Monday morning. Friday evening, after a hard week of trying to get departments or individuals to cooperate, or using university service facilities that were designed to meet the needs of academic operations rather than research, and in dealing with the idiosyncrasies of our main sponsor, the federal government, integrated research looks less rosy. Research however, is a hardy activity and, like a hollyhock seed on an ash dump, it seems to get along in spite of unfavorable surroundings.

When I came to New York University nine years ago, there was practically no cooperation in research among the departments. However, there was one group under Renato Contini doing interdisciplinary research with a status roughly parallel to an academic department but without academic responsibilities. This work went under various names such as human engineering, biomechanics, or special engineering. Here medical people, social scientists, engineers, and physical scientists have worked together harmoniously for many years. Such work has accounted for about 15 or 20 per cent of the work of the research division. This, it seems to me, is an excellent way to organize interdisciplinary work on a university campus. It is interesting to note further that some interdisciplinary work now handled directly between departments and also some academic work have grown out of these activities.

Courses in the form of a prosthetic education program that resulted from this work, as a matter of interest, are given by the Post Graduate Medical School of New York University. Sidney Fishman, a psychologist employed by the College of Engineering and director of our Prosthetic Devices Research, played an important role in developing these courses. Other courses that are related to this work now are given also in industrial engineering.

I have also mentioned the fact that some of the interdisciplinary work of the academic departments was initiated by the group under Contini. This involved some statistical mathematicians who originally were in the interdisciplinary group, but who were later moved to the mathematics department. These mathematicians have done excellent cooperative work with several of the academic departments, both before and after the transfer.

Since most of our interdisciplinary research is under Contini's supervision, I asked him what he thought was the greatest problem in supervising such research. He felt that the language barrier presented the greatest difficulty. Furthermore, the scientists and engineers stress clarity and precision and seem to think the social scientists vague and inconclusive. However, with

one project that had been operating for ten years, a considerable rapport had developed.

Aside from the interdisciplinary work initiated in Contini's group, there is another example of such work in the College of Engineering. This involves air pollution research. Here meteorologists, aerodynamicists, sanitary engineers, and chemical engineers from the academic departments work together when needed. A committee coordinates the work. This arrangement is satisfactory, but it seems to apply to best advantage when most of the projects



FIGURE 3

clearly belong in the individual departments and the areas of cooperative or interdisciplinary work are not too extensive.

Insofar as the future of interdisciplinary research is concerned, it seems desirable as a matter of background briefly to review some of our current activities.

Within the Research Division, we have had for the past ten years a number of projects that were truly interdisciplinary. Since 1948 we have been conducting research and evaluation of prosthetic devices. In this program a broad range of skills are involved, including those of engineers, medical scientists, physiologists, psychologists, therapists, and prosthetists. Both the hook and the hand in FIGURE 3 were developed by engineers from information made available by physiologists, and the glove was developed by mechanical and chemical engineers working together with industrial designers on the

basis of information furnished by psychologists. FIGURE 4 shows an amputee walking on a specially prepared runway in which are installed a pair of force plates. The engineer is observing the amputee and controlling recording devices for objective data on the amputee's gait; a medical evaluation expert is observing the amputee for subjective interpretation of his gait.

Along similar lines we have worked on the development of a multiple-purpose iron lung, where the engineers were required to work in very intimate

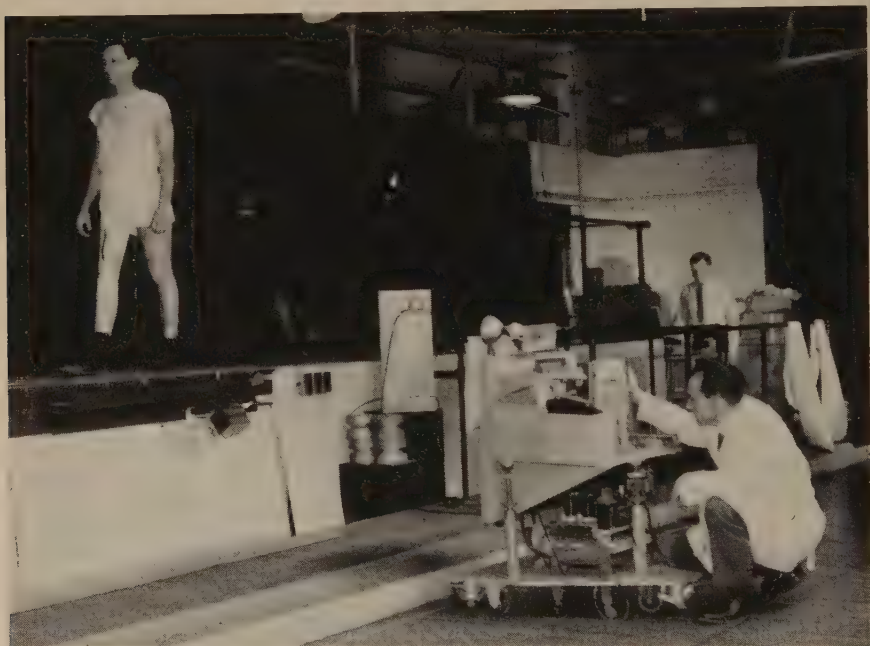


FIGURE 4. Amputee on special runway.

association with the medical scientists. Also we have developed several types of wheel chairs and have assisted in the planning of other special types of devices for disabled people; again an area of research in which the physical and medical sciences worked together. For the military we have worked on the development of a harness for an airborne litter to reduce the damage done to airborne patients. In this instance we had to work with the medical scientists to find out what numbers of cases were being airborne, with the physiologists to find out the tolerance to pressure on the part of the patient, and with the psychologists for the means of restraining psychiatric cases. FIGURE 5 shows the device the engineers designed on the basis of this information and after a series of studies and tests. The litter permitted a maximum support for the wounded patient with a minimum possible damage in the event of an airborne crash.

Again for the military we have studied a number of communication systems. We have worked on airborne combat information centers and on radar

defense centers. Here it was necessary to enlist the skills of the experimental psychologist and those of the electronic engineer to achieve the most effective results. FIGURE 6 shows a psychologist of our so-called human engineering group working with an assistant on a manual direction finder in a room shielded against radio noise by walls of copper mesh.

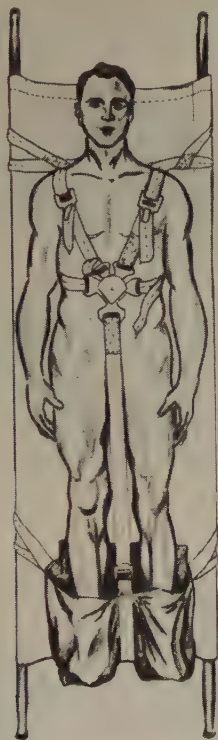


FIGURE 5. Litter for transporting casualties.

In FIGURE 7 is shown a pressure capsule designed as a high-altitude animal container for aeromedical studies. This is a borderline case; we produced the unit for medical people.

Our air pollution research calls upon the services of many disciplines. In FIGURE 8 may be seen aerodynamicists of the Guggenheim School of Aeronautics, New York, N. Y., using a special wind tunnel to study some of the aerodynamic factors in specific air pollution problems.

FIGURE 9 shows an engineering mechanics professor studying the stresses and strain in human bones. This work, of course, is carried on in conjunction with medical people.

This brief glimpse at what we are doing will serve to indicate some of the basic considerations that are forcing an ever-increasing amount of interdisci-



FIGURE 6. Studying the human factors that permit a skilled operator to discriminate against noise and undesired signals in a manual direction finder within a room shielded against radio noise.

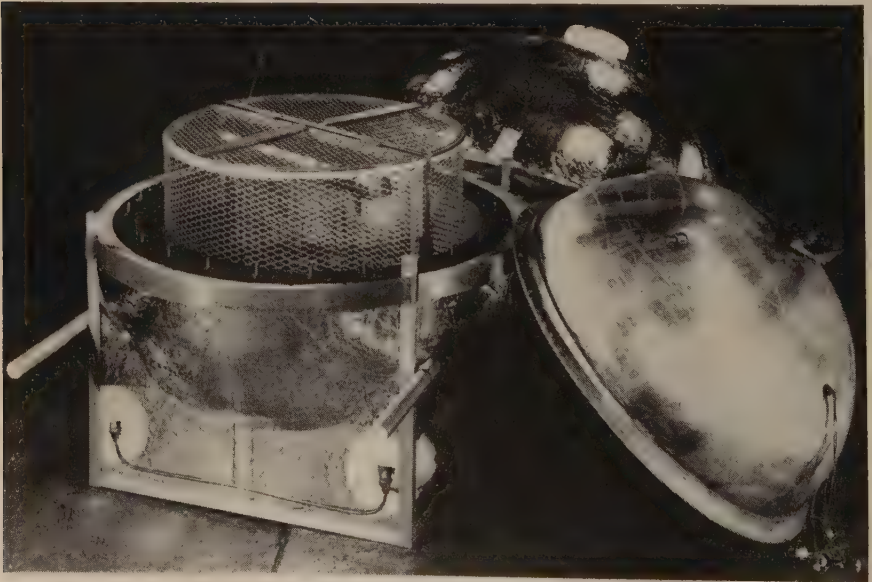


FIGURE 7. Pressure capsule.



FIGURE 8. Wind tunnel for air pollution problems.



FIGURE 9. Stresses and strain in human bones.

plinary research. The recent rapid strides of science and engineering have tended to outstep the capabilities of human beings. Advances in aircraft, nuclear energy, automation, and electronics have created such complex problems that it is necessary to consider again the capabilities of man to handle the intricate problems involved. In military application the increased speed of mechanical operation is so great that man is often the limiting factor, and every effort must be made to get the most out of him. All of this indicates that more and more interdisciplinary work can be expected in the future.

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Part III. Neuromuscular Dysfunction

ANALYSIS OF THE HEMIPLEGIC GAIT*

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INTRODUCTION

Patients with abnormalities of gait are frequently encountered in the practice of medicine. Although their clinical appearances have been described extensively, the use of objective, instrumental recording methods for a quantitative evaluation of the biomechanical factors involved and of the corrective measures applied is relatively recent.

Most of the studies carried out have been directed at the normal person and the patient with various orthopedic disabilities. Of recent investigators, Steindler and Schwartz and their associates¹⁻¹¹ especially must be commended for their work. Schwartz and Heath³ reviewed the status of the study of gait up to 1932, and their paper is worth examination. More recently the patient with neurological disease has been investigated.¹²⁻¹⁴

The force plate, an instrument designed especially for the analysis of gait patterns, is now available and seems to have extremely valuable potentials. Devised by Elftman¹⁵ in 1938, it has grown into a complex apparatus for measuring the ground reactions developed during walking, that is the forces developed during the period of contact of the lower extremity with the ground during the stance phase. Simultaneously, using an interrupted-light camera similar to that developed by Marey,¹⁶ a stroboscopic photograph of the test subject can be obtained for the period during which the ground reactions are recorded. This photograph records the relative positions of the various segments of the lower extremity to each other and in space throughout the walking cycle. The joint moments, that is, the angular forces developed at the joints, can be calculated by correlating the ground reactions with the exact position of the limb at that time. By means of the electromyograph, a 16-lead recording oscillograph, the electrical potentials generated in 7 of the most important muscle groups in the lower extremity are recorded. This establishes the pattern of muscular activity during both the stance and swing phases of gait.

These methods have been employed extensively in the study of amputees and are directed primarily at the design and perfection of artificial lower limbs that will duplicate the gait characteristics of the normal individual.^{17, 18} The methods are potentially useful, however, for the study of any gait aberration.

In the practice of neurology and rehabilitation, the patient with hemiplegia presents probably the most common and serious medical, social, and economic

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problem. Conservative estimates have placed the number of hemiplegics in the United States alone at 1,250,000.

Considerable interest has been directed toward the primary treatment of this handicap and the rehabilitative measures applicable for a reduction in severity. As gait abnormalities are obvious, emphasis has been placed upon their correction, but quantitative analyses that might afford a more objective evaluation have not been carried out extensively. For some time it has been felt that objective studies might be of value in determining the basic motor patterns responsible for the gait disturbance. By this means, the effect of gait training and the influence of the short leg brace, commonly prescribed to afford greater stability to the patient and to counteract the talipes equinovarus position of the foot, also could be more objectively evaluated.

Patient Material

The patient material consisted of 19 patients with moderately spastic hemiplegia ascribed to antecedent cerebral vascular accidents that occurred from 6 months to 3 years prior to the study. All 3 methods were applied to the gait analysis of seven patients. A total of 11 patients was studied by the force-plate techniques, and a total of 15 by electromyography. In addition, control records were obtained from normal subjects.

Test Equipment

Force plate. The force plate was a specially suspended platform mounted flush with a 40-foot wooden walkway and placed approximately at its center. Readings could be made in either walking direction.

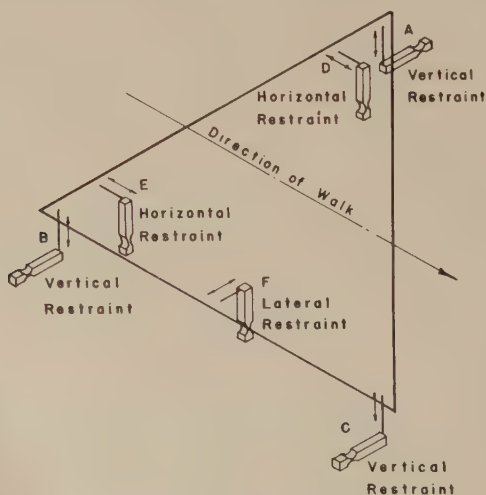


FIGURE 1. Schematic diagram of the dynamic force plate.

Bolted to a cement base, the force plate was composed of 2 equilateral right triangular sections fitted so as to form a square roughly 40 inches on a side. Each plate half was independent in its mounting. The mounting in each

case consisted of 6 support beams, each attached to the plate top with a turnbuckle (FIGURE 1).

Each of these restraints measured forces in only 1 plane, and permitted free motion in the other 2. The beam link insets were so arranged that 3 (one at each apex of the triangle) supported the plate vertically and recorded the vertical forces. Two restraints recorded the fore and aft forces, and 1 the lateral forces. Each bending beam was reduced in section locally to localize and intensify the stress produced by plate loading (FIGURE 2). At this site, strain gauges were mounted. They were temperature-compensated, and they

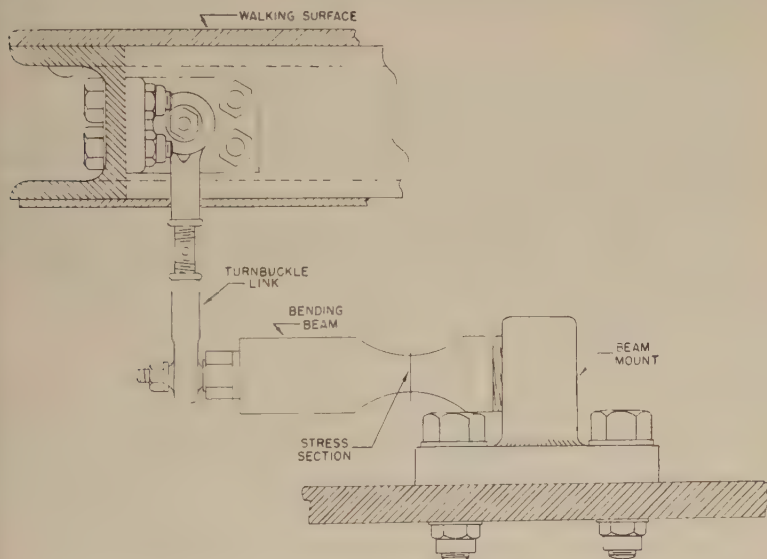


FIGURE 2. Detail of the vertical restraint and its bending-beam assembly.

recorded both compressive and tensile stresses. A deflection of the bending beam altered the resistance to an electric current flowing through the strain gauge proportionately to the stress developed. This change unbalanced a Wheatstone bridge circuit, was amplified, routed through a string galvanometer, and recorded photographically. Through calibration, the forces developed in pounds could be calculated. FIGURE 3 represents a characteristic record. The sums $A + B + C$ yield the total vertical force developed; $E + F$ the fore and aft forces; and D the lateral force.

Interrupted-light camera. This device consisted of a rotating shutter providing intermittent exposures. It was so coupled that it intergrated the exposures with the corresponding force-plate reading. The photographic system was designed to be activated by the subject as he passed in front of a photoelectric cell, stepped on the force plate, and then finished the exposure by passing in front of a second photoelectric cell.

The rotating shutter was driven by a geared synchronous motor at 20 rps. A sector in the shutter permitted one exposure per revolution. The exposure

time was $\frac{1}{500}$ sec. on Kodak Super Panchro-Press Type B film. Micro-switches were arranged to record a deflection on the force-plate oscillography record each time an exposure was made. Timing cams were so adjusted that the sequence could not be started or finished in midexposure.

Oscillograph. A type PA Universal Oscillograph manufactured by Westinghouse was utilized. It is a mechanically operated electromagnetic instrument, measuring electrical quantities as a function of time on photographic paper. The frequency range varies from zero or constant quantity to a frequency greater than 4200 cps; the response is flat to within 2 per cent for frequencies below 1250 cps.

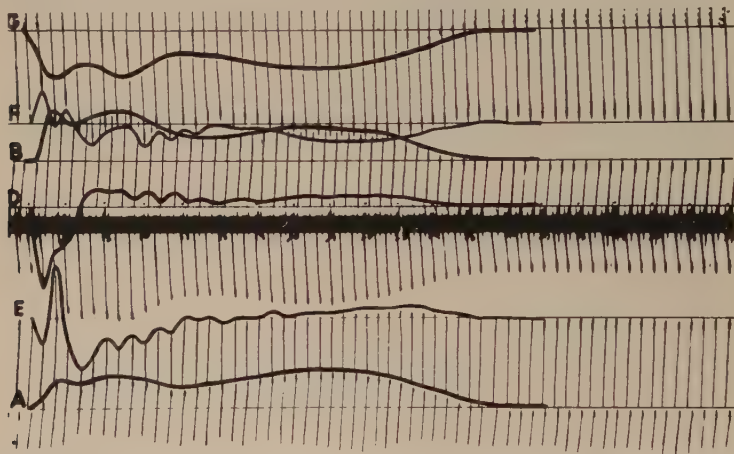


FIGURE 3. Typical oscillograph record marked to show the successive forces developed as a continuum.

The seven galvanometers were recorded on Kodak linegraph 697 paper carried in a 200-foot magazine. Development procedures were those conventionally applied to low contrast enlarging paper. After washing, the record was dried in a rotating Fedco dryer, care being taken to avoid ferrotyping of the record face.

Projector. The oscillographic records were enlarged using the opaque feature of a Bausch & Lomb projector, type 41-23-81. It was necessary to construct a special carrier, permitting precise alignment. Enlargement of approximately ten times allowed accurate measurements of amplitude to be made.

Electromyograph. A Medcraft, 8 channel, ink-writing oscillograph, commonly used for electroencephalography, was employed.

TEST PROCEDURE

Force-Plate and Stroboscopic Studies

The subject was clothed in black tights. A white stripe was mounted on the shoe and joined to a similar white stripe sewn to the tights, outlining the

axis of the lower limb. Joint markers (ankle, knee, hip) were placed on the stripe.

The subject walked at a self-chosen comfortable pace. Several preliminary runs were conducted; during these the subject's starting point was positioned to enable him to strike the plate in as natural a manner as possible. This procedure was simplified by the large triangular shape of the plates. The subject with a short stride was positioned on the walkway so as to strike

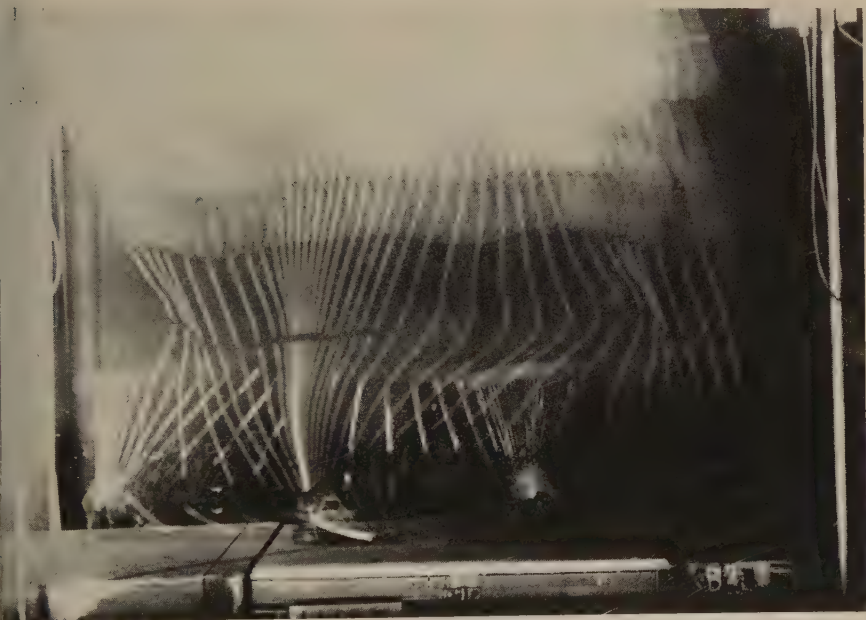


FIGURE 4. Stroboscopic photographs of a left hemiplegic, braced, walking across the force plate. The right leg is being analyzed.

near the apex of the triangle, while the large-stride subject was positioned to strike near the broad base. As the subject ambulated, the oscillograph drive was started and the rotating shutter of the interrupted-light camera was switched on. When he crossed the path of the photoelectric cell the camera shutter was opened and simultaneously, the time marker was activated. After the plate had been crossed, a second photoelectric cell was activated, the camera shutter was closed, and the time marker was cut out. The resultant picture showed the relative position of each segment of the lower limb at $\frac{1}{20}$ -sec. intervals throughout the walking cycle (FIGURE 4).

By the use of this technique, information was gained relative to one lower extremity in the course of one run. It was necessary to have the patient repeat the procedure, walking in the opposite direction, to gather comparable data for the other leg. In each study, information was obtained for the nonparetic as well as the paretic limb. Whenever possible (in six patients), the gait patterns in both extremities were evaluated with and without a brace



FIGURE 5. Short leg, double-bar brace, with 90-degree stop and stirrup attachment.

on the patient. In all the cases the brace was a short leg double bar with stirrup attachment, foot plate, and a 90-degree stop (FIGURE 5).

EVALUATION

Evaluation is a lengthy and complex affair. It was necessary to make calibrations of the force plate every operation day and to apply corrections to the data for numerous factors, including interaction, photographic lens aberrations, photographic paper distortion, parallax, and photographic perspective. We were concerned primarily with the total vertical pressures. By correlating these data with measurements of the corresponding knee-joint angles computed from the stroboscopic photographs, the knee movements, that is, the angular force acting at the knee, were plotted for the period of the stance phase.

Electromyographic Studies

Small skin electrodes (metal disks of three-fourths-inch diameter) were applied with adhesive tape over the muscles to be examined. Thin wires connected these electrodes to a channeling box which the subject carried on his back. A 10-foot cable connected the box with the oscillograph (FIGURE 6). This arrangement allowed the subject to walk freely back and forth for a distance of 20 feet. Two microswitches attached to the sole of the shoe pro-

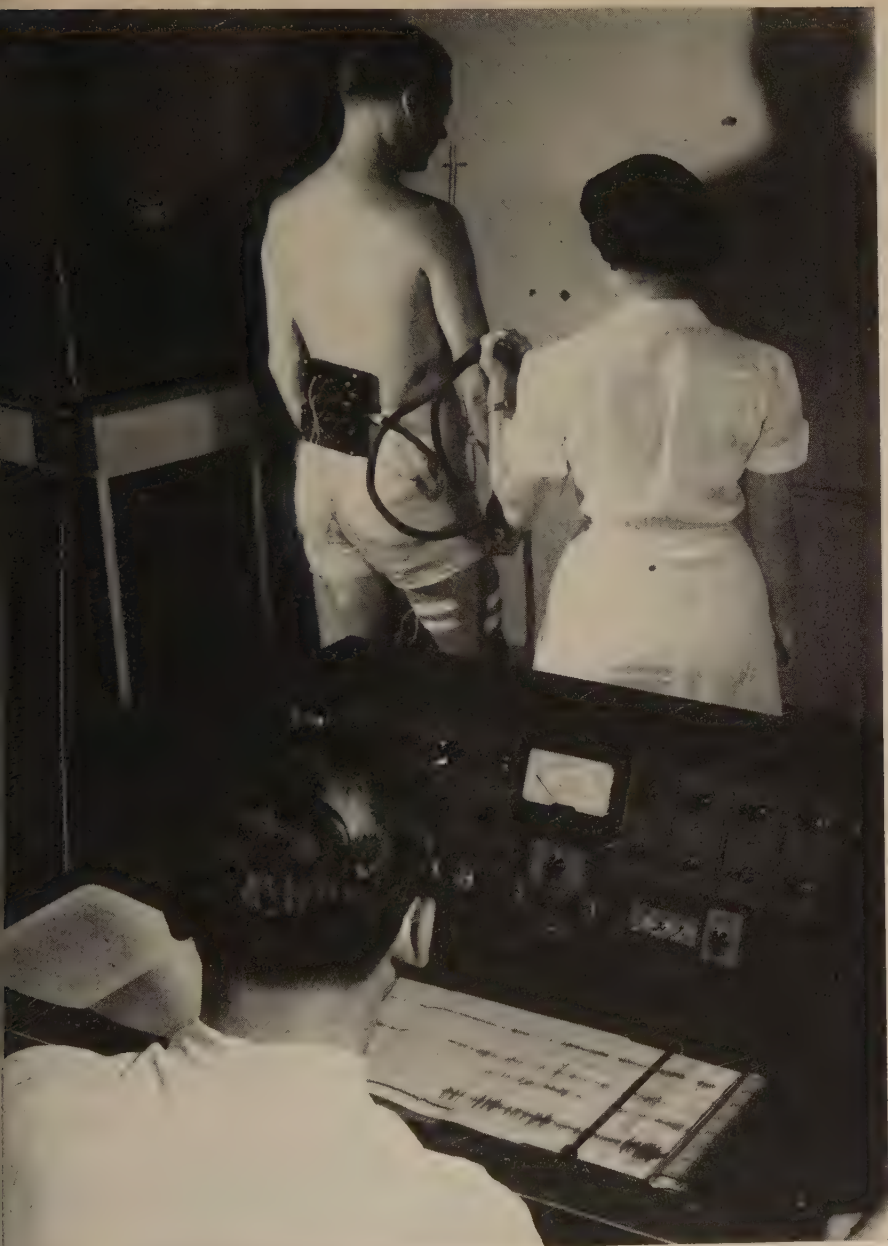


FIGURE 6. Technique of electromyographic recording. The muscle action potentials are picked up by metal electrodes attached with adhesive tape to the skin over the muscle. Thin wires connect these electrodes with a channeling box. The latter is connected to the recording machine by a 10-foot cable, thus allowing the patient freedom to walk a distance of 20 feet.

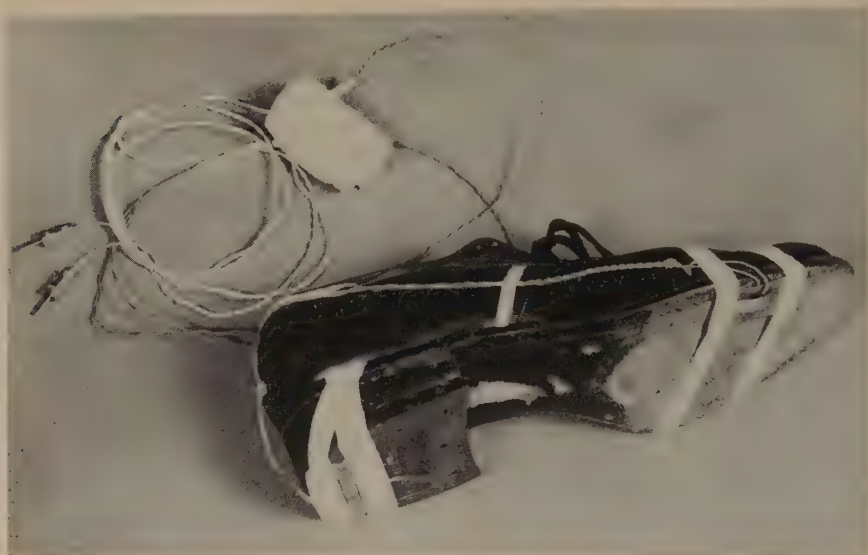


FIGURE 7. Recording of stance and swing phase. Microswitches attached to the sole and heel of the shoe are connected to one channel of the oscillograph, where they produce a signal at the beginning and at the end of the stance phase.

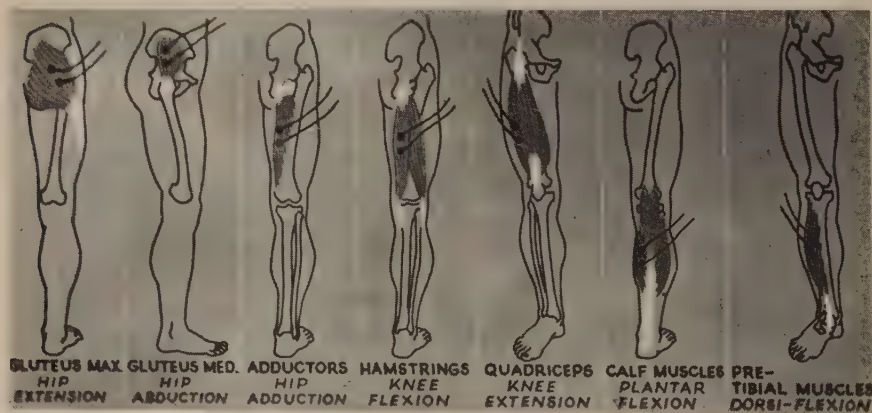


FIGURE 8. Main muscle groups in the lower extremities studied electrically.

duced signals that demarcated the swing and the stance phase (FIGURE 7). These signals were recorded in one channel of the oscillograph. The other channels recorded the electric activity of the seven major muscle groups of the lower extremity (FIGURE 8). A preliminary study showed complete synchronism in the contraction of all muscles of the same group during walking. Therefore, only one muscle was chosen from each group for the recording of action potentials in the following way: (1) hip extensor group, gluteus

maximus; (2) hip abductor group, gluteus medius; (3) hip adductor group, adductor longus; (4) knee flexor group, semitendinosus; (5) knee extensor group, vastus lateralis; (6) calf muscles, inner head of gastrocnemius; and (7) pretibial muscles, tibialis anticus.

Since the mechanical effect of muscular contractions coincides, for all practical purposes, with the electric activity in the contracting muscle, the electro-myogram allows us to analyze the pattern of muscular activity.

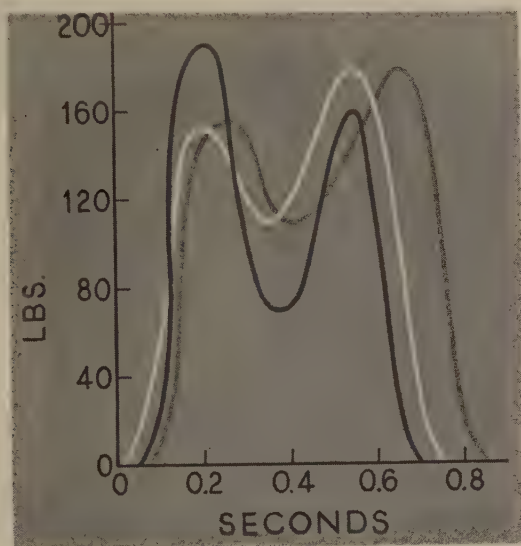


FIGURE 9. Vertical pressure curves of three normal subjects.

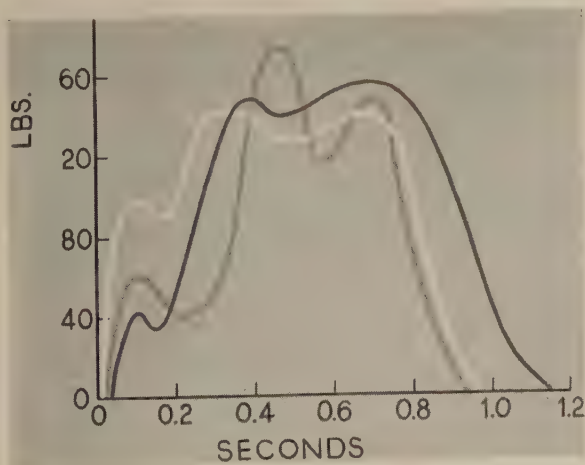


FIGURE 10. Vertical pressure curves of the paretic limb of three hemiplegic subjects.

Results

Vertical loads. The significant findings during the stance phase were analyzed, and the vertical acceleration of the body was recorded by the force plate as it became weight bearing. FIGURE 9 reveals the typical pattern of the normal subject, which is characterized by two peaks, corresponding to

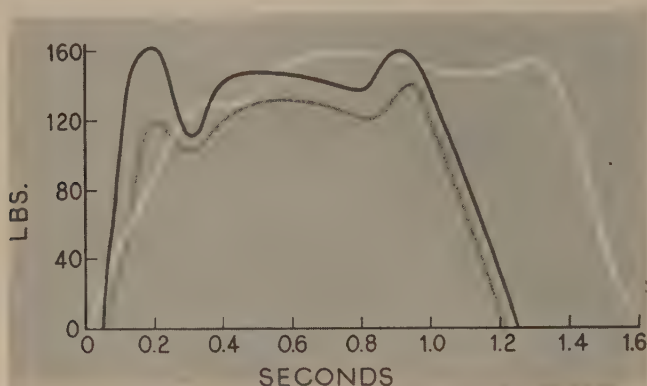


FIGURE 11. Vertical pressure curves of the nonparetic limb of three hemiplegic subjects.

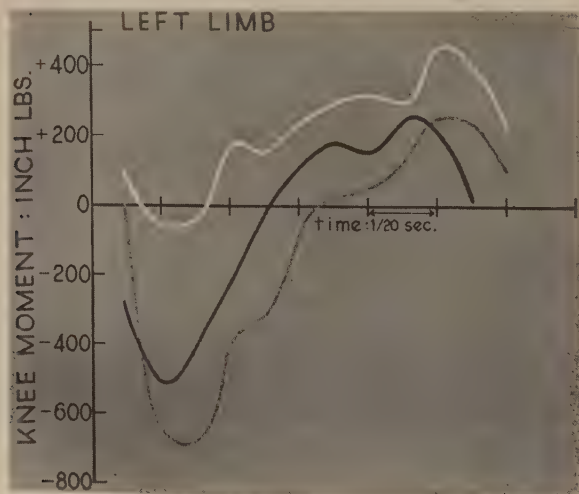


FIGURE 12. Knee-moment characteristics of three normal subjects.

the beginning and end of the swing phase of the opposite leg. In the normal pattern the vertical load increases rapidly as contact with the ground is made, reaching a peak load greater than the weight of the subject. This attests to an acceleration greater than g . As the area of contact moves forward from the heel and the foot is more solidly placed, the process of swinging the other leg through is initiated; at this time the vertical load drops to a minimum

value. As the swinging extremity passes the plane of the center of gravity, the vertical force is again increased and reaches a maximum at the beginning of the double-stance phase. In the typical hemiplegic record obtained from the paretic lower extremity (FIGURE 10) the vertical pressure curve is more

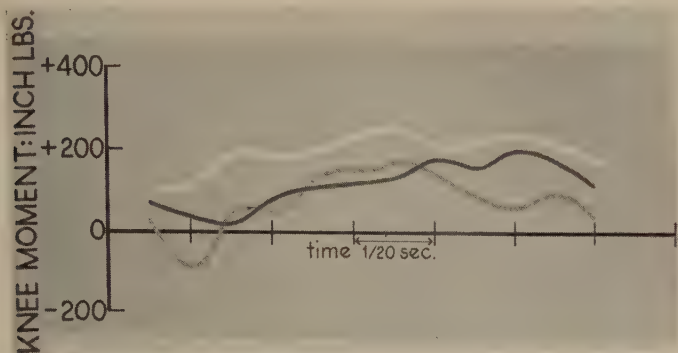


FIGURE 13. Knee-moment characteristics of the paretic limb of three hemiplegic subjects.

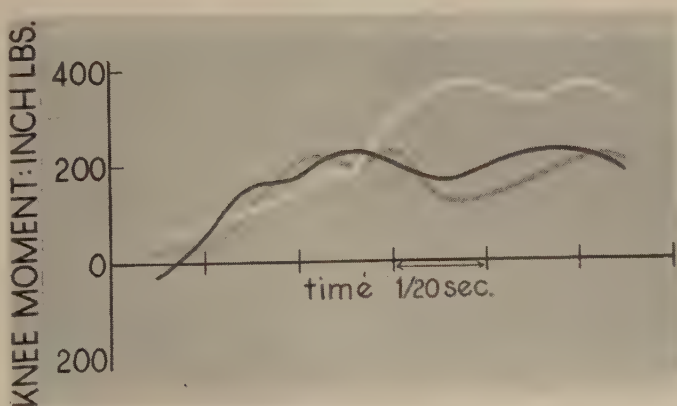


FIGURE 14. Knee-moment characteristics of the nonparetic limbs of three hemiplegic subjects.

variable and has an initial low peak. In general, the trends are similar. This graph indicates that the vertical load build-up is accomplished in a steplike manner. Concomitant studies of the stroboscopic photographs disclosed that the normal subject strikes the ground with the knee in full extension and then absorbs the resultant shock by a slight knee flexion of seven degrees, which is correlated with the negative knee moment (see below). The hemiplegic strikes the ground similarly with the knee in full extension, but there is little or no subsequent knee flexion. The resultant graphic representation records the shock acceleration noted as a third load peak.

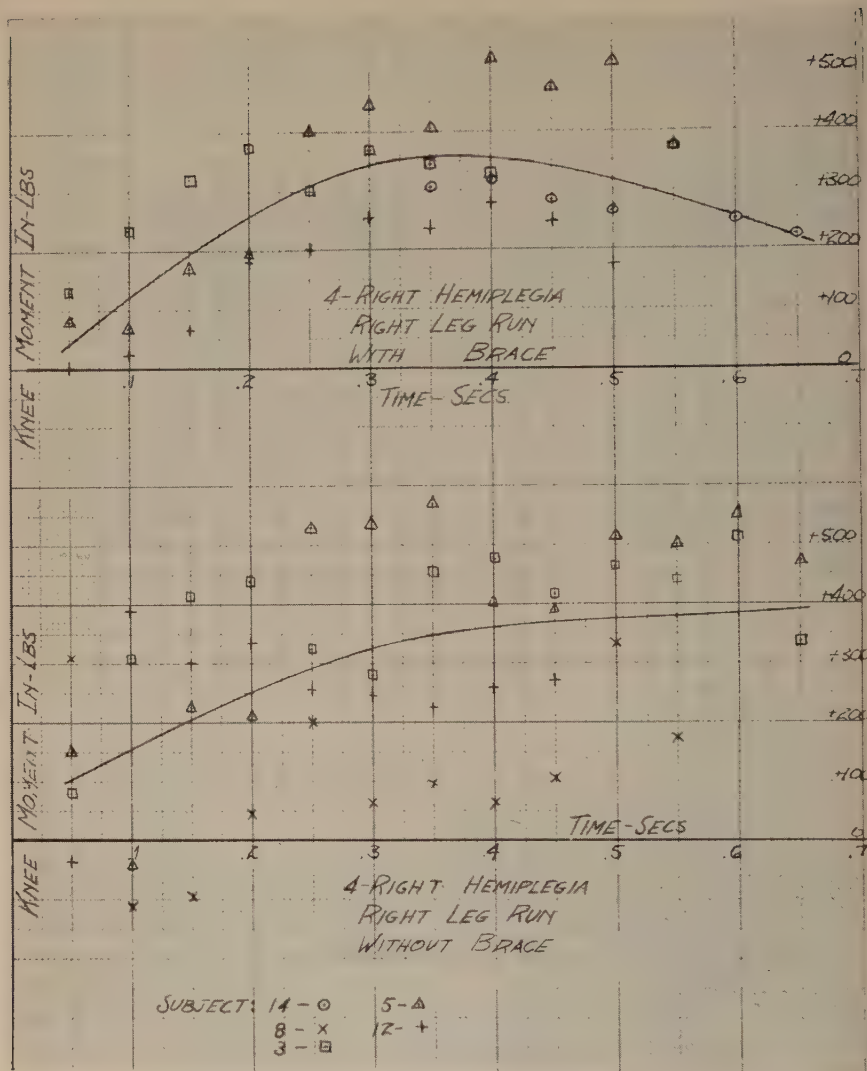


FIGURE 15. Knee-moment characteristics of the paretic limb of the hemiplegic in the braced compared with the unbraced state.

A study of the nonparetic leg of the hemiplegic (FIGURE 11) revealed the same characteristics noted on the paretic side. These findings, that is, the abnormal motor patterns observed in the paretic and nonparetic leg, were not significantly altered by brace wearing and did not appear to be correlated with the degree of clinical recovery.

Knee moment. The knee-moment characteristics of the hemiplegic differ considerably from those of the normal subject. In the latter the graph of

the knee moment is *S* shaped, with an initial negative component followed by a positive one (FIGURE 12). The negative knee moments correspond to the early stance phase. Correlated stroboscopic photographs show that, when the leg has become weight bearing, the knee flexes and sustains a negative or unlocking knee moment. As the body center of gravity rides over the plane of the foot position in the stance phase, the knee moment becomes

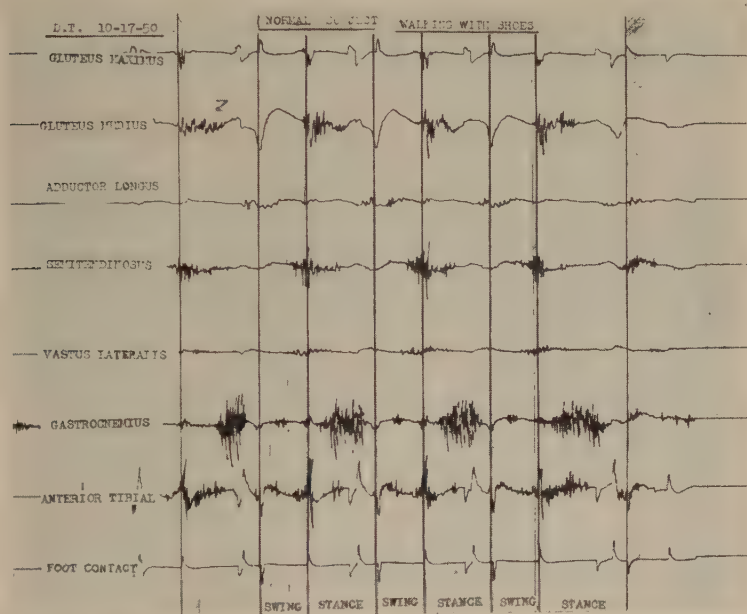


FIGURE 16. Electromyographic pattern of normal gait. At the transition from swing to stance all muscles contracted. During the first third of the stance phase the gluteus medius, gluteus maximus, adductor longus, and the semitendinosus are active. The gastrocnemius contracts in the middle of the stance phase. At the transition from stance to swing only the adductor longus is active. During the swing phase the anterior tibia shows variable activity, and frequently there is a burst of activity of the gastrocnemius during the middle of this phase.

strongly positive and approaches a magnitude of 300 to 500 inch-pounds. In the hemiplegic the knee moment in the paretic leg is strongly positive throughout the cycle (FIGURE 13). The knee moment characteristic of the nonparetic leg is similar to that demonstrated on the paretic side, that is, a large positive moment present throughout the stance phase (FIGURE 14). This characteristic persists whether the short leg brace is worn and seems independent of the extent of clinical recovery or the side of the body involved (FIGURE 15.)

Electromyographs. In the normal subjects a consistent pattern of electric activity was found (FIGURE 16). Only one muscle group, the calf muscles, started to contract in the middle of the stance phase.

This group was the most active in the normal gait, as shown by the high amplitude of its tracing. Six muscle groups, including the hip muscles, the quadriceps, and the hamstrings, showed electric activity during the transition from the swing to the stance phase. Of these muscles, only the gluteus medius continued to contract beyond the middle of the stance phase. The

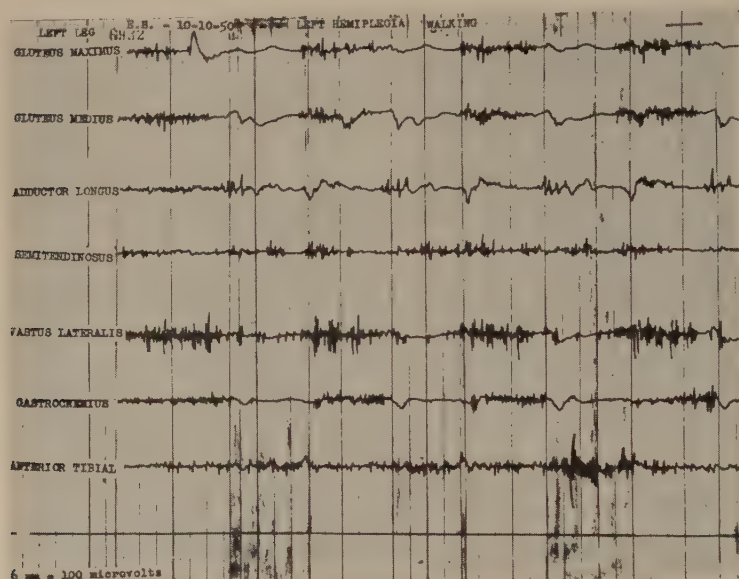


FIGURE 17. Electromyographic pattern of the involved lower extremity in a patient with marked hemiparesis, showing (1) prolonged contraction of the semitendinosus and vastus lateralis during the stance phase, (2) a low amplitude of the gastrocnemius, (3) activity of the gastrocnemius from the end of the swing phase to the end of the stance phase, and (4) generally decreased muscular activity and prolonged swing phase.

others ceased contracting within the first third of this phase. At the transition from stance to swing, the adductors and, in some cases, the hamstring group contracted. During the swing phase only the pretibial group was found to be active. Frequently a burst of activity of the gastrocnemius was found in the center of the swing phase. In the normal subject the patterns of electric activity in both legs were identical.

In patients with hemiplegia the paretic extremity showed a prolonged swing phase and decreased activity of all muscles (FIGURE 17). The most active muscle groups in this extremity were the quadriceps and the hamstrings. Their contraction began at the final portion of the swing phase and lasted until the end of the stance phase. The amplitude of the tracing of the calf muscles was low and uniform. The onset of their contraction coincided with the beginning of the stance phase, and the cessation with the end of this phase. The hip muscles deviated only little from the normal pattern.

The nonparetic limb of the patients with hemiplegia showed a shortened swing phase and increased activity of all muscle groups, especially of the

gluteus medius (FIGURE 18). The timing of electric activity resembled that of the paretic more than the normal limb. For instance, the quadriceps and hamstring groups were active throughout most of the stance phase. Further-

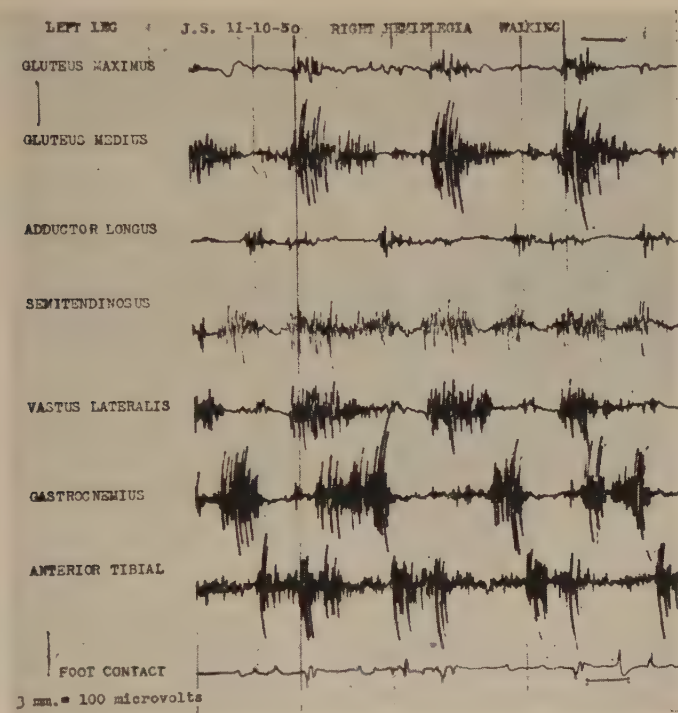


FIGURE 18. Electromyogram of the nonparetic leg of a patient with hemiparesis. This pattern is characterized by (1) generally increased muscular activity, (2) shortened swing phase, (3) prolonged activity of the semitendinosus and vastus lateralis, and (4) contraction of the gastrocnemius from the end of the swing phase to the stance phase.

more, the tracing of the calf muscles was uniform in amplitude and began, in most instances, with the stance phase.

DISCUSSION

An unanticipated feature that became obvious from these studies was the observation that there are changes of a similar character in motor performance in the nonparetic as well as the paretic leg of the hemiplegic. In attempting to explain this bilateral phenomenon, it was natural to question whether the stiff-knee effect of the paretic leg associated with the lack of negative knee moment set up a mechanical situation that was transferred into the nonparetic limb. To test this hypothesis, the findings obtained from the force-plate and stroboscopic studies of a series of above-knee amputees were examined. Each of these patients had been fitted with and trained in the use of an artificial lower extremity. With this type of prosthe-

sis it was impossible for the subject to develop a negative knee moment during the stance phase; nevertheless, the ground reactions on the uninvolved side were comparable to those of the normal subject (FIGURE 19).

One is tempted to ascribe neurophysiological significance to the fact that bilateral patterns of motor abnormalities are obvious with predominantly unilateral brain damage. A number of observations suggest that the cerebral lesion itself directly alters the functional capabilities of the nonparetic or "normal" limb. It is a clinical fact that the hemiplegic patient frequently

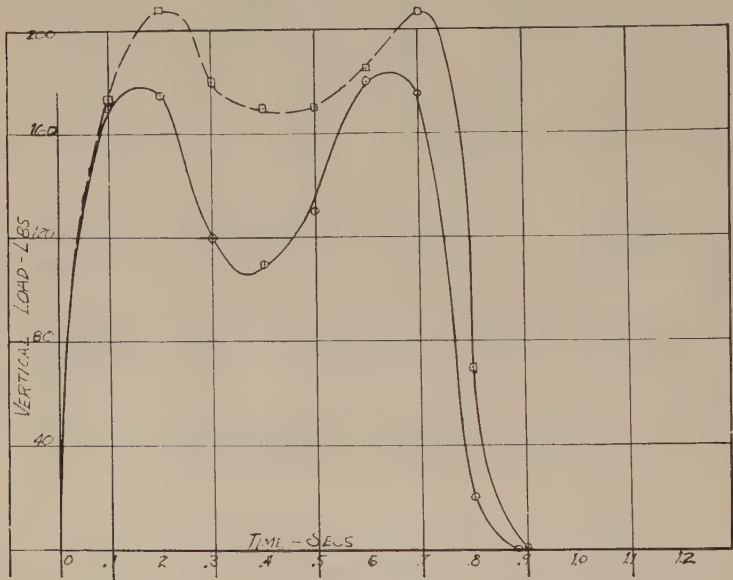


FIGURE 19. Vertical pressure curves of the uninvolved side of two above-knee amputees ambulating with artificial limbs.

shows a defective performance; that is, a dyspraxia in his ability to carry out alternative moments of the nonparetic limb, although not to the degree seen on the paretic side.¹⁹ Bergman *et al.*²⁰ demonstrated that the knee jerks in the nonparetic limb are abnormal in many hemiplegics. Schuster and Pineas²¹ observed grasp abnormalities in the nonparetic upper extremity of the hemiplegic.

This accumulated evidence suggests that, although mechanical factors may play a role in the production of the bilateral patterns of motor abnormality in the patient with a unilateral brain lesion, other explanations must be considered. It is conceivable that these changes in motor performances may reflect the capabilities of the brain to undergo a reorganization of its functional capacities; in attempting to compensate for the deficiencies imposed by the pathologic process, the residual functional capacities may be performed at a lesser level of efficiency or in an abnormal fashion. Another possibility raised is that these are bilateral cerebral representations of motor patterns.

Stimulation experiments in lower animals by Hering,²² Tower,²³ and others, which resulted in bilateral movement patterns, would tend to support the latter hypothesis. Undoubtedly these are not the only possible explanations. Acceptance of one does not preclude the validity of or the acceptance of the other.

Another interesting feature noted in this study was that neither the wearing of the short leg brace nor the period of retraining significantly altered the

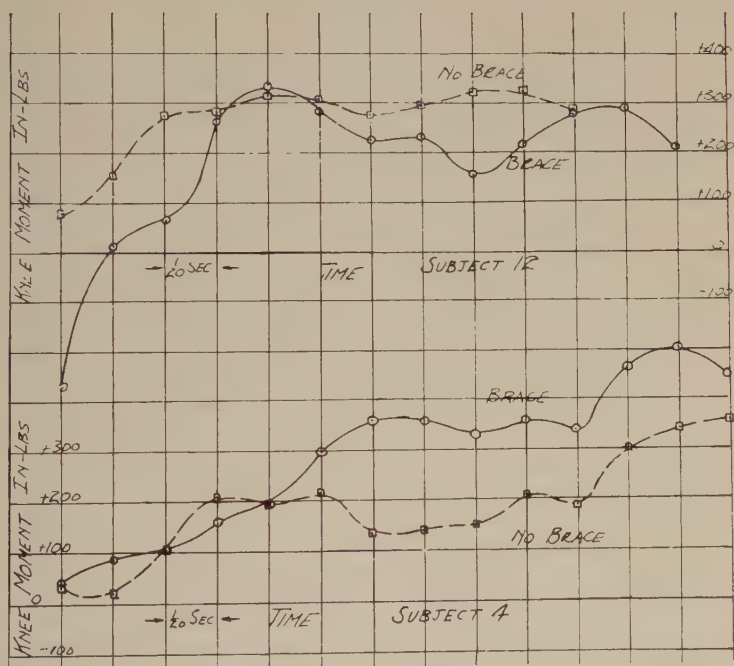


FIGURE 20. Knee-moment characteristics of the nonparetic limb of two hemiplegics with the paretic limb braced and unbraced.

observed motor patterns (FIGURE 20). From this it must not be assumed that these procedures are valueless in improving the gait of the hemiplegic patient. Unfortunately, the nature of this study was such that only the stance phase could be investigated adequately. Since the maximal benefit of the brace seems to occur immediately prior to the stance phase, in that the abnormal position of the foot is corrected, insuring the patient a stable support on which he can bear weight, final objective evaluation must await a more detailed and comprehensive gait analysis in which both phases can be considered. The psychological benefit the patient derives from the assurance that his paretic limb is relatively stable and that there is a lessened tendency to fall may be considerable.

What clinical significance do these studies have? The uniform occurrence of bilateral motor abnormalities in the patient with hemiparesis demands a

reemphasis of the bilateral, reciprocal nature of gait. In gait retraining the movement patterns of the nonparetic as well as the paretic extremity must be observed carefully. Teaching the patient merely to lift his leg and to bend the knee of the paretic limb results in an abnormal pattern. A more physiological one requires a "push off" to initiate the swing phase, which is correlated with the forceful contraction of the gastrocnemius muscle.

Despite the fact that the basic patterns of abnormality are similar, each hemiplegic patient's gait problem is a highly individualized one. It is not within the scope of this paper to consider the technical aspects of the gait-retraining program itself. However, before such a program can be considered, many factors, such as the following, must be analyzed for *both* lower extremities: (1) the patient's sense of balance; (2) the position and stability of the foot at the time of initiation of the stance phase; (3) the presence or absence of complicating foot conditions, for example, corns, calluses, and deformities; (4) the presence or absence of normally associated and involuntary movements, for example, arm swing, ankle clonus, tremors; (5) knowledge of the patient's kinesthetic sense appreciation, that is, position sense in such areas as the toes and feet; (6) the strength of the intrinsic musculature; (7) the state of muscle tonicity, that is, normal, flaccid, or spastic; (8) the muscle actions during both stance and swing phases, noting especially whether the gastrocnemius push off is present; (9) an estimate of the knee-moment characteristics; and (10) the influence the shoe and/or the brace has on the basic patterns.

When these have been determined, a meaningful gait program can be prescribed correctly.

SUMMARY

The gaits of a series of hemiplegic patients were investigated objectively, utilizing the force-plate stroboscopic and electromyographic techniques. An analysis of the records disclosed abnormalities of motor performances of a similar character in the nonparetic as well as the paretic lower extremity. The short leg brace or a period of gait retraining did not significantly alter the patterns of abnormality observed. Some of the factors that must be considered before instituting a program of gait training are enumerated.

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PSYCHOLOGICAL ADJUSTMENT PATTERNS OF THE DISABLED

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Introduction

A continually increasing interest in the rehabilitation of the chronically ill and disabled has resulted in the fact that problems associated with the psychological adjustment of such patients now receive more attention. Researches have not always been as fruitful as might be desired, but we at least can derive some satisfaction from the fact that the empirical application of the clinical skills of psychologists and psychiatrists has been enthusiastically reported by many workers in the rehabilitation field.¹⁻⁵ While the major portion of this paper is concerned with the deficits in our psychological research methodology on the rehabilitation process, it is important to bear in mind that this is not intended to detract from the fine contributions of the past and present in the area of applying existing psychological knowledge empirically to the care of the rehabilitant.

Keeping in mind the good work being done, let us consider some of the more common deficiencies observed in psychological investigations of disability and its effects upon the patient:⁶⁻⁸

(1) A tendency to fail to establish clearly the relationships between premorbid and postmorbid behavior.

(2) Excessive dependence upon existing psychological instruments even when their validity and reliability are inadequately established for use with the disabled. At times these instruments may not even have established validity and reliability of significant degree on any population sample.

(3) A failure to correlate findings obtained even by such crude and inadequate instruments with the psychophysiological behavior of the patient. Evidence of the relationship of the results of such tests to alterations in the homeostatic mechanism is, therefore, not available.

(4) A concomittant indifference to the development of new instruments that might prove useful in the derivation of indices of such factors as the patient's motivation, level of aspiration, and threshold of frustration. These factors have been suggested as possible vectors influencing psychological adjustment in the disabled.

(5) A disregard for the essential need to establish suitable outside criteria for the patient's adjustment. The assumption that responses to tests in and of themselves actually constitute sufficient evidence of the patient's ordinary behavior is often the source of generalized and all too often spurious and unsubstantiated conclusions.

We shall consider each of these deficiencies, as well as some examples based upon past and current researches. Some extension of our knowledge

regarding the psychological adjustment patterns of the disabled may result therefrom.

Relationship of Premorbid and Postmorbidity Behavior

The presence of a catastrophic disabling illness often leads to a serious distortion of our interpretation of the patient's behavior. In our society one may lose sight of the realities of the patient's conduct during the years that preceded his illness. This leads to the investment of the patient with a "halo" as a gesture of sympathy or as a means of overcoming guilt feelings engendered by our own attitudes toward the disabled.

This attitude appears to be transferred even to the scientifically trained psychologist, as evidenced in studies in which the patient's morbid or post-morbid behavior is investigated, while conduct prior to onset is given little or no attention. The psychological assessment of adjustment of the patient in these instances consequently is without an established base line. The patient's behavior not only is a function of his present catastrophe, but is dependent upon his earlier experiences and his genetically influenced characteristics.

It is unfortunate that some psychological investigators fail to recognize the necessity of using suitable control subjects to minimize the error of assigning to the illness and the resulting disability a meaning that is basically related to the patient's premorbid background. Had adequate controls been used, one would suspect that some of the so-called personality changes considered as specifically associated with tuberculosis, poliomyelitis, and psychosomatic illness might more properly have been interpreted as responses to stress of catastrophic proportions that might be expected to yield similar reactions in the intact individual.

We recognize the factor of control as an important element in the design of research. Nevertheless, we find noncontrolled studies that report the tuberculous personality, the personality of the accident prone, the polio personality, and the like.⁷ Such reports are seldom based upon a view of the patient as a total entity; they chiefly emphasize a delineated segment of the patient's life without consideration of the patterns of adjustment that have characterized his entire life. Perhaps an even greater source of error is the fact that such interpretations lead to generalizations that create the stereotyped concept that all patients suffer from a specific disease or disability. For example, the patient forced to spend much of his daily life confined to an "iron lung" unavoidably must be influenced by the very nature of this life-sustaining apparatus. This influence can be studied since, in recent years, many new respiratory aids capable of helping the patient to breathe have been developed. These have the advantage of being smaller, less physically confining, and often allowing the patient relatively greater ranges of mobility. Patients able to use these devices instead of the iron lung should have demonstrably modified attitudes toward themselves and their milieu. A careful investigation of the different types of respiratory support currently available, and of changes in attitudes of the patients as they are allowed to use the chest respirator, the rocking bed, and similar aids, would be valuable in helping us

understand the impact of the characteristics of each device upon the patient. Of course, adequate controls for such factors as background, type, and extent of illness would be essential.

The careful studies of Abt, Fishman, and others, on the psychological factors involved in adapting prostheses to amputees lead us to hope that similar consideration can and will be made in the field of orthotics.⁹ We may thus obtain a more complete understanding of the patient's attitudes toward assistive devices. It would be especially valuable to be able to differentiate between patients who will and will not make optimal use of such help before their psychological resistance has been minimized or eliminated. One factor likely to increase the prognostic value of such observations is a consideration of the patient's premorbid adaptation to new and different learning situations. An important element in learning to use prosthetic and orthotic devices is the readiness of the patient to accept the realities of his disability. There is reason to believe that this is at least partially predictable in terms of the patient's acceptance of reality as demonstrated prior to his illness. If the predictability of this behavior can be established, those who seek to help the patient will be better able to provide the necessary additional psychological help for the more resistant patients. The ultimate result would be greater success in the rehabilitation process and for a greater number of patients.

Inadequacies of Psychological Instruments Used in Studying the Disabled

An inordinately large amount of psychological research upon the adjustment patterns of the disabled has made use of measuring devices often inadequately validated and poorly adapted to use with this population.

It is obvious to trained researchers that certain standards of validity and reliability applicable to the sample studied must be met before any instrument can be used properly. The fact that such standards have been established for a general segment of the population does not necessarily mean that they are equally applicable to a special population sample. Neither does it mean that they have the same significance when interpreted, if the population sample is not comparable to that on which the standards were established. L. M. Terman and others clearly recognized this when they sought to use the Binet test on children in the United States. Obviously the French children upon whom the original scale of Binet was used not only spoke a different language, but exhibited an entirely different frame of reference. As a result, much alteration, much restandardization and revalidation was necessary before the test was acceptable elsewhere.

At times, however, psychologists have used the Stanford-Binet and other measures on seriously disabled individuals without proper consideration of the comparability of this group with the standardization sample. If the goal is that of comparing the disabled to the able-bodied in the performance of requirements established for the latter, this may be justified. If establishment of the potentialities of the disabled in terms of their optimal psychological level of function is sought, however, then it would be desirable to use suitable adaptations of these tests on which reliability and validity against appropriate criteria are established.

Let us consider only a single example among many that might be given. Frequently an investigator seeks to measure personality characteristics of disabled individuals by using either projective or nonprojective tests, or both. Most of these instruments were designed to measure characteristic patterns in able-bodied individuals. In interpreting results obtained with such instruments when administered to less-than-able-bodied persons, this question arises: Are the findings correctly analyzed when we deal with them as though the change in physique, the altered body concept, and other alterations related to these factors were not present? Should a subject with gross body distortion who reports many anatomical responses in the Rorschach be viewed as an able-bodied subject making many anatomical responses? Should someone who reveals more than the ordinary number of anxieties over physical health, because his physical health has actually been severely threatened, be viewed in the same light as a healthy person who has had no such threat, but who gives similar responses? I think all of us must agree that this should not be the case, yet many investigators have used instruments in just this manner. In other circumstances some workers have accepted the frequent "normal" response from the disabled as indicating their essential normal attitudes. In reality, is it normal for a disabled individual to give a normal response to a series of questions they have learned to regard as the "expected socially acceptable answer"?

The answer would seem to be an uncertain one. The use of these tests must be established both as to reliability and validity on the specific population. However, a study of the literature reveals the paucity of such efforts even today. There is a very real need not only to establish the validity of the present-day armamentaria of psychological instruments used on the disabled, but to develop new and more suitable instruments appropriate for use with such a population.

One should not overlook the fact that the very nature of the test procedure places the examinee in competition, as it were, with those against whom the test was standardized. Only when one believes the patient is qualified as a participant in such competition should we place him in such a role. Thus, one could conceivably administer tests, standardized on a general population, to a patient who is considered close to or at the point of maximal rehabilitation. Such tests then give us a lead into a prognostication of the outcomes of his assumption of his role in society. When the patient is being studied to determine the effect his disability is having upon *him*, however, he should be studied in a matrix of behavior characteristic of an acceptable sampling of patients with a similar or comparable disorder. Such an approach would tend to reduce false conceptions regarding the impact of disease on the patient's psyche, would help us to a better understanding of the individual patient, and would help to establish a sounder psychological program for his benefit.

Need for Correlation of Elements of Psychological Adjustment with Physiological Factors

When accident or disease alters the individual's physique there may be concomittant physiological alterations. Oftentimes temporary or even per-

manent changes in metabolism, cardiovascular function, neurological disturbance, or some other function may result. The effect of such physiological shifts upon the psyche is often unknown or disregarded. There is little doubt that physiological alterations such as these may exert profound effects upon the homeostatic mechanisms of the body which, in turn, are likely to produce resultant psychological alterations.

Modern advances in our knowledge of biochemistry and physiology have taught us that changes result from the original source of trauma. In addition, the stress introduced as a concomitant of this pathological process is capable of setting up indirect effects upon the body physiology closely paralleled by psychological changes that affect the homeostatic mechanisms even further.

In spite of this, psychologists seldom have included in their studies on the disabled any correlative material that might relate psychological variance from the norm with the patient's altered physiology. Elsewhere we have called attention to this phenomenon, with specific reference to alterations in the respiratory pattern of patients with bulbar and bulbospinal polio. It is no less pertinent, however, to what may occur in cardiac disease, in cardiovascular-renal disturbances, in cancer, tuberculosis, and a whole host of metabolic, neurological, and other disturbances of the normal physiology associated with chronic illness.

The tendency for research psychologists to treat changes in the disabled patient's psyche as though they actually had no relation to altered physiology would seem to lead to ultimate disregard of the etiological factors that produce these changes. This attitude is as unjustified as the failure of a clinician to heed the importance of psychological elements in considering physical disturbance. As a matter of fact, this may very well be one of the sources of the lack of acceptance by the physician of the psychological elements in disease.

While we should not minimize the importance of the external environment as a source of the patient's psychological reactions to disabling disease, there appears to be no justification for regarding this as the sole factor. Due consideration of the altered physiology and its effect on the emotional balance and control of the patient may lead to a more intelligent solution of the total problem.

*Need for Development and Utilization of Psychological Instruments
for Measuring Untapped Factors in Predicting the
Adjustment of the Disabled*

In past and current researches dealing with adjustment problems of the disabled very little consideration has been given to those facets of personality most likely to play an important part. Motivation, level of aspiration, and frustration tolerance, for example, are probably key factors in the determination of whether or not the patient will ever try to adapt himself to the realities of life. Even when these factors have been recognized as significant, the investigators have been disinclined to attempt their measurement and correlation with ultimate outcomes in the rehabilitation process.

Admittedly, the existing measures of these psychological characteristics

leave much to be desired. This does not excuse the failure to utilize them, crude as they may be, while seeking to improve and extend their applicability. Certainly the methods developed by Kurt Lewin and others provide some bases on which to begin the solution to this problem. While some of the early experimental studies may not per se lend themselves to use with the disabled, there is opportunity for their adaptation. We can anticipate the development of new procedures that will test personality factors such as these without taxing the physical capacities of these patients beyond their limits.

Provided their validity is established, the continued use of paper and pencil tests with the disabled may be permissible. However, there should be provision also for studying motivation in a manner that calls for utilizing the undamaged elements of the physique. Frustration tolerance and levels of aspiration, as they apply to the disabled individual engaged in some suitable degree of physical activity, likewise must be investigated carefully. It would seem that too much emphasis has been placed upon the patient's "paper and pencil personality" without recognition of the fact that his most serious problems are those closely associated with difficulties in adjustment to the much more dynamic elements of his milieu. The task of attaining acceptable mobility, ready response to environmental stimuli, and the like cannot be reduced to an equivalent paper-pencil reaction.

While the use of the Rorschach, the Minnesota Multiphasic Personality Inventory, or other means of tapping these dynamic elements may be partially justified, they often fail to reveal facets of behavior connected with the maximal activity one can expect of the patient. Unfortunately they tend to underemphasize the patient's potential capacity to resolve many of his frustrations, including those related to movement. Furthermore, they fail to assess the change in his drives as he gains confidence and understanding of his actual capacity.

Psychologists whose researches are based on static appraisal of the patient must content themselves with guessing what he can actually do. On the other hand, psychologists working with the physician interested in bringing the patient from the *status quo* into active utilization of his impaired body augmented by his undamaged capacities will find that psychological measurements that measure the patient's activity tolerance are likely to enhance the predictability of ultimate adjustment. This is a crucial factor in determining the outcomes of rehabilitation.

The psychological plan for research on the adaptation of the disabled patient should include, to an increasing degree, provision for such studies and for their correlation with suitable criteria of successful rehabilitation.

Need for Suitable Criteria of Patient Adjustment

Our great need today is not only for the development of good psychological measuring tools but also for the establishment of suitable outside criteria by which they may be validated. If we are ever to achieve reasonable clinical success in prognosticating the psychological rehabilitation of the disabled, we must spend a great deal more time and effort in determining how good psycho-

logical adjustment can be recognized. Once this is accomplished, the validation process will follow established research design.

We have been inclined to accept such criteria as test performance, as the opinions of rehabilitation workers regarding the success or failure of the disabled on the job, and as job satisfaction. Perhaps some of these criteria are suitable, but often they are not properly weighted in such terms as the pre-morbid behavior of the patient, the extent to which the patient had a role in selecting his present job, the variety of opportunities supplied the patient, or the degree to which the patient's potentialities are utilized. Furthermore, many patients will not be engaged in ordinary employment situations. Some will work at home or in special "sheltered workshops." Others will not, in any serious sense, be capable of work but will have gained, as a result of rehabilitation, greater ability to handle their personal needs, such as the capacity to feed themselves, and to manage their toilet requirements and other activities of daily living. Criteria, then, must be established in terms of the maximal attainment in physical capacity that can be expected of the patient.

Whatever the ultimate decision regarding criteria, they must be defined sufficiently to make it possible for the research worker readily to recognize their presence or absence. Inadequate or inappropriate criteria lead to false generalizations and create a spurious basis for future prognostication.

The establishment of criteria is often the most difficult task in research. Perhaps that is why so many early studies have led to doubtful or inaccurate conclusions. Regardless of the difficulty, psychological researchers working on the adjustment characteristics of the disabled must be increasingly aware of their responsibility. All attempts at validation should be made upon criteria that are truly reflective of the behavioral characteristics being measured. A clearer understanding of the psychological characteristics that differentiate the "successfully" rehabilitated from those "not so successfully" rehabilitated may help to establish these criteria upon a firm foundation. These data will be of enhanced value to the extent that we can reduce subjective impressions of outside observers and increase the objective elements that may be more accurately reported.

Summary

Growth of interest in the rehabilitation of the ill and injured has called for extension of training and research in medicine and its allied professions. Among the professions engaged in serving in the arena of rehabilitation services, psychology has made many fundamental contributions. Thus far the most predominant role of the psychologist has been that of applying empirically his knowledge of human behavior to the development of sound rehabilitation practice. It would seem that this is indeed proper behavior, since social, vocational, as well as emotional readaptations of the disabled patient call for the applied experience of the psychologist to help him overcome the difficulties associated with the patient's acceptance of himself and of his social milieu and in providing him opportunity for the attainment of a full measure of satisfaction.

There is, however, a need to increase both the accuracy and extent of our knowledge with regard to what happens psychologically to the disabled patient. This can be accomplished only by improving the tools by which the psychologist measures the patient's capacities and his adaptability. This means that more and better research based upon the use and interpretation of valid, reliable measurements of these patients must be developed. Suitable criteria for successful outcomes of rehabilitation need to be established so that guesswork will be displaced by good prognostic devices that will aid not only, in giving improved service to these disabled individuals, but in reducing wasted efforts to accomplish the impossible for those who are psychologically unable to make use of such assistance. This is especially important when we consider the fact that rehabilitation personnel and facilities are limited and that knowledge of the practical limits of rehabilitation efforts is important to patient and practitioner alike.

The necessity of developing useful methods for making these prognostications has prompted me, in this paper, to be somewhat negativistic in stressing past research deficits and possible means of overcoming some of them. If the outcome is positive in the direction of improving the *status quo*, the criticism that may result will be of little moment.

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OBJECTIVE RECORDING AND BIOMECHANICS OF PATHOLOGICAL GAIT

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One of the most frequently studied problems in biomechanics is locomotion. In its simplest form, locomotion consists of displacement of the subject's center of gravity from one place to another. In the more complicated form, locomotion also involves the maintenance of balance. All multiform methods of animal locomotion such as swimming, sliding, crawling, walking, and running basically are sinusoidal oscillations produced by summation of segmental rotations of body segments. These rotations are transformed by the body into linear translation movement.

In everyday life we can observe many different ways of walking. The particular manner in which locomotion is performed is called gait.

Gait differences in human beings have attracted the attention of observers for centuries. A wide spectrum of different gaits exists, from the funereal gait of a priest to the goose step of marching German soldiers. Gaits are determined by body build, age, sex, occupation (sailors and regal gait), nationality, and geographical location. Variations from normal gait stem from slight deviations in the function of the locomotion mechanism. The proper function of the mechanism of locomotion depends upon closely integrated action of the subject's bones, muscles, and the peripheral and central nervous system. Disorders at any level give rise to characteristic disorders that result in pathological gait. Biomechanical analysis of pathological gait, when considered with other signs and symptoms, may assist in providing important information for better diagnosis.

The problem of locomotion is a classic example of a case where a knowledge of normal activity is necessary to understand the causes or effects of abnormalities. Many distinguished authors have made significant contributions to a better understanding of normal human locomotion. The names of Weber,⁵⁴ Marey,³³⁻³⁵ Carlet,¹¹ Fischer,^{9, 25} Amar,¹ Basler,³ Bernstein,⁴⁻⁶ Steindler,^{48, 49} Schwartz,⁴³⁻⁴⁷ and Elftman¹⁶⁻²¹ should be mentioned as pioneers in this field. The fundamental investigations of the biomechanics team of the University of California, Berkeley, Calif. under the direction of Eberhart and V. Inman^{22, 23, 40} also should be mentioned.

Studies on the biomechanics of pathological gait are very scarce and mostly scattered in specialized publications. The names of Vierordt,⁵³ Demy, ¹⁵ Momen,³² Kektchejev,²⁹ Scherb,⁴² Nicolaeff,³⁷ Steindler,⁵⁰ Hartley,²⁶ and Wortis⁵⁶ should be cited. A number of reports on the biomechanics of the amputee's gait have been published by the Prosthetic Devices Study of New York University under the direction of Contini and Fishman.^{12, 13}

A review of the literature indicates that only a few of the published analyses of pathological gait are based on proper walking time measurements and ade-

quate graphic recording of paths and velocities of the limb movements involved. In spite of many centuries of medical observation, an examination of medical dictionaries,³⁶ handbooks of diagnosis,^{31, 39} and special works, such as the excellent books of A. Steindler,^{48, 51} shows that, at present, no uniform morphologic description or uniform classification exists. The aim of this paper is to suggest a replacement of subjective observations of the pathological gait by objective motion and force recordings^{8, 27, 28, 30} that allow subsequent biomechanical analysis. Such recordings also will permit an objective and systematic follow-up of disintegration or reconstruction. I propose that, in such investigations, the areas of temporal factors, kinematics, and kinetics be studied. In addition, I suggest that measurements of metabolism of gaits be made to determine energy requirements of various pathological gaits.

Temporal Factors

Walking has its own temporal organization or pattern. Each temporal pattern consists of two or more phases. The relative duration of these phases is indicative of the gait under given conditions.

The temporal pattern of walking has been studied less than its kinematics and kinetics. A prime reason for this has been the lack of proper and convenient recording instruments that would permit accurate measurement of successive series of small walking time intervals. To overcome this obstacle, New York University's Prosthetic Devices Study has developed a special method for recording the components of walking time.

Basically, the instrumentation for the time-interval recording is a low-potential direct-current circuit that is closed at the successive foot contacts with ground and opened at the following swings (FIGURE 1).

The equipment consists of a metal sheet, 50 ft. long, 2 ft. wide, fixed on a walkway. Foil strips of the same material, placed under the shoes of the subject, are connected by wires to an electric plug at the waist. The plug is joined by a cable cord to a battery and a channel of a recording oscillograph. The cord runs over a pulley system that permits the subject to walk in either direction and provides electric contact throughout the length of the walkway. If the subject stands on the metal sheet with one foot in contact, the circuit remains open until the heel of the second foot comes into contact with the sheet. The circuit then closes and remains closed during the time interval when both feet are in contact with the ground (double-support time). At the moment either foot is removed from the metal sheet and swings forward (swing-phase time), the contact is disconnected and the circuit interrupted. Thus, while the subject is walking, the oscillograph records in turn the duration of double-support time and swing-phase time.

After one or two trial runs, the subject is asked to walk in both directions at normal, slow, and fast speeds, and the time recordings are made. Simultaneously with the time-interval recording, the instantaneous horizontal velocity of the subject's trunk and the step lengths are recorded.

A tachograph is used to record the horizontal velocity of the subject's trunk during level walking. The tachograph consists of a small DC generator

connected to an oscillograph channel. The generator is activated by a cable cord attached to the subject's belt at approximately the center of gravity of the body. During walking, the cord passes over the pulley system and drives the DC generator. The amplitude of the output signal is directly proportional to the instantaneous velocity of the subject's trunk.

The step length is determined from the distance the tachograph cable cord travels during 1 step. Since the circumference of the generator pulley is exactly 6 inches, 1 revolution of the pulley represents a 6-inch displacement

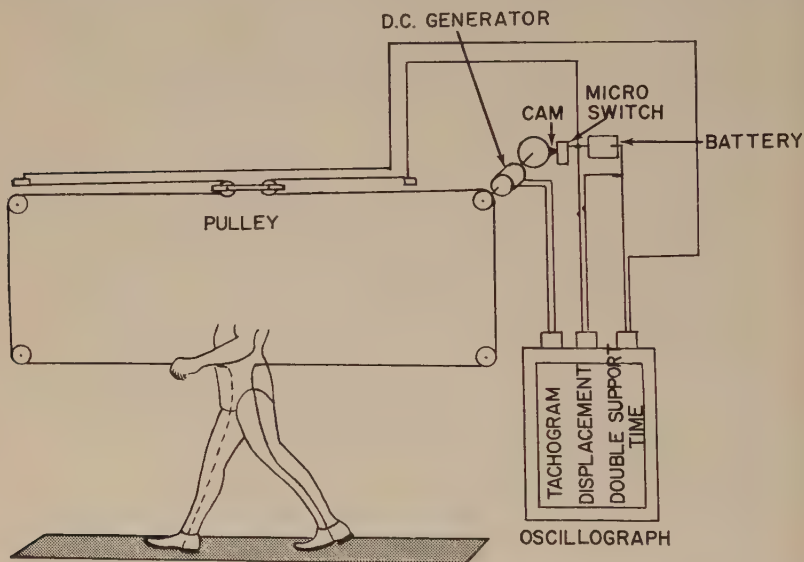


FIGURE 1. Instrumentation for recording time intervals, instantaneous horizontal velocity, and step lengths.

of the subject's body. The pulley has a cam arrangement that activates a microswitch connected in series with a battery and 1 oscillograph channel, so that the 6-inch distances are marked simultaneously with the step-time recordings.

In walking, the time interval between two successive heel contacts of the same leg is called the period or stride time. Each period consists of stance-phase and swing-phase time. Step time is the interval between the heel contact of one leg and the following heel contact of the other leg.

FIGURE 2 shows how, from the recorded double-support time and swing-phase time, the stride, step, and stance phase times are determined. All these components are measured for each leg separately for all strides and steps at all three speeds. The following criteria are then studied:

Cadence. The number of steps per time unit (minute or second) in walking is one of the basic characteristics of gait. The limits, range, and the mean values are indicators of the quality of gait.

To obtain background information about the characteristics of the cadence

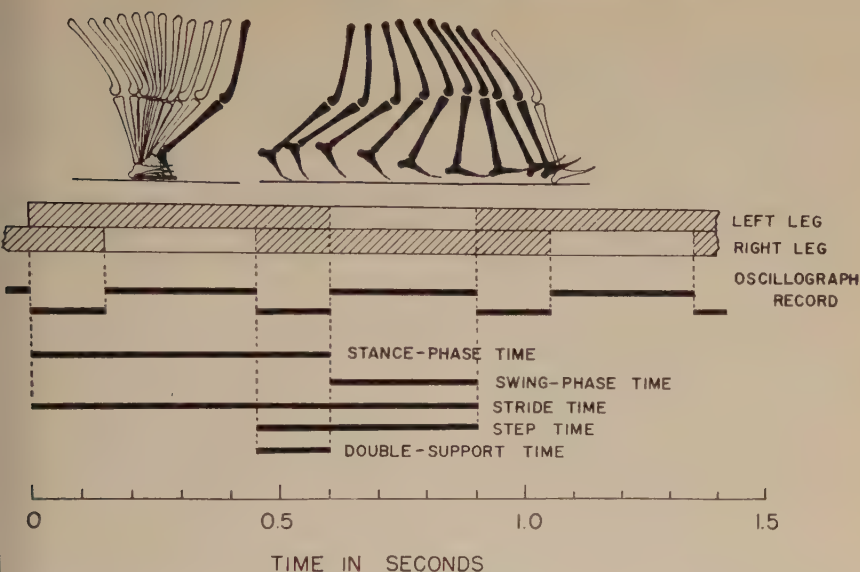


FIGURE 2. Determination of the stride-, step-, and stance-phase times from the recorded double-support and swing-phase times.

of normal walking, observations were taken on 936 normal subjects walking on a New York City street. Cadence and speed of walking were determined with a stop watch, measuring time and counting the number of steps taken over a 20-meter distance. The results of our observation are shown in TABLE 1.

TABLE 1
CADENCE OF WALKING

Cadence	Class limits in steps per minute	Percentage of total
Very slow.....	78 -100	10
Slow.....	100.1-107.0	20
Normal.....	107.1 -117.6	40
Fast.....	117.7-125.0	20
Very fast.....	125.1-144.0	10

The arithmetic mean (M) was 112.5 steps/min. and the standard deviation = 9.8 steps/min. The standard error of the mean was ± 0.32 steps/min., so that $M = 112.5 \pm 0.32$ steps/min. The variability of cadence (v) was:

$$v = \frac{100 \cdot \sigma}{M} = 8.71\%$$

FIGURE 3 shows that a definite difference in mean values of cadence does exist between the 936 pedestrians and the subjects with pathological gait. At normal speed, the mean cadence of the 936 pedestrians was 112.5 steps/min.; for the sample of 12 above-the-knee amputees, 90.5 steps/min.; for a hemiplegia patient, 98 steps/min.; and for the postpoliomyelitis patient, 93 steps/min. The slowest observed cadence of the 936 pedestrians was 78 steps/min.; the lower limit of cadence of the sample of above-the-knee amputees, 70 steps/min.; for the hemiplegia patient, 82 steps/min.; and for

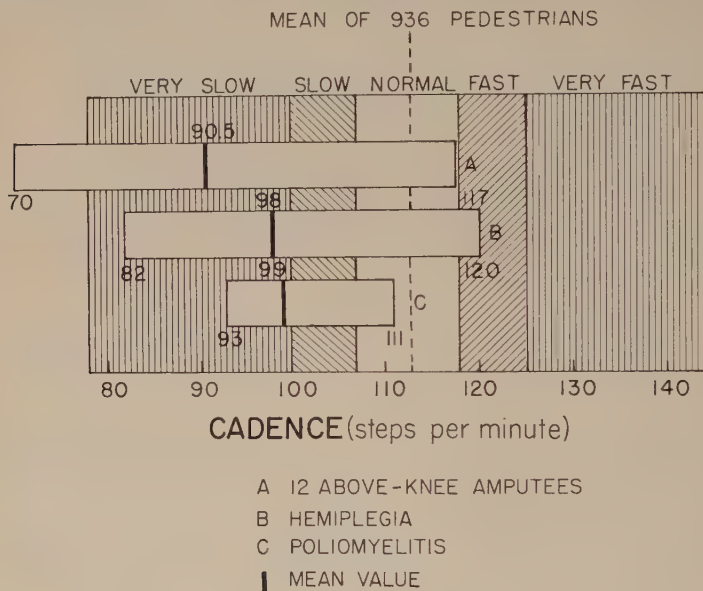


FIGURE 3. Cadence.

the postpoliomyelitis patient, 93 steps/min. In the attempt to walk fast, the above-the-knee amputees were able to reach only 117 steps/min., that is, range of normal speed for our pedestrian sample. The postpoliomyelitis patient achieved only 111 steps/min., which is less than the mean value for normal speed. Therefore, the range of cadence was 66 steps/min. for the pedestrian sample; 47 steps/min. for above-the-knee amputees; 38 steps/min. for hemiplegia patients; and 18 steps/min. for the postpoliomyelitis patient.

In general, the cadence of pathological gait as compared to normal gait usually has a narrower range and a lower mean value for normal speed, which is the optimal cadence when energy expenditure is least.

Motility index. Bertalanffy,⁷ in his book *Theoretical Biology*, has shown that, in animals, the average pulse and breathing rate are in an inverse relation to the cube root of the body weight. My investigations on walking characteristics of 750 male and 250 female subjects in Germany showed that the cadence patterns generally follow the same rule, but are also dependent upon age. To characterize these relationships, an index of motility is used.

The index is determined for each age group as the arithmetical mean of the products of the cadence at normal speed and the cube root of body weight. It permits comparison between the observed subject's cadence and the expected cadence for his age and weight group. Since motility and vitality are closely related, it seems that the index of motility can serve also as an indicator of vitality. As shown by FIGURE 4, the index of motility for males reaches its maximum for the age group between 25 and 30 years. The corresponding age group for females is between 18 and 23 years. At present, no

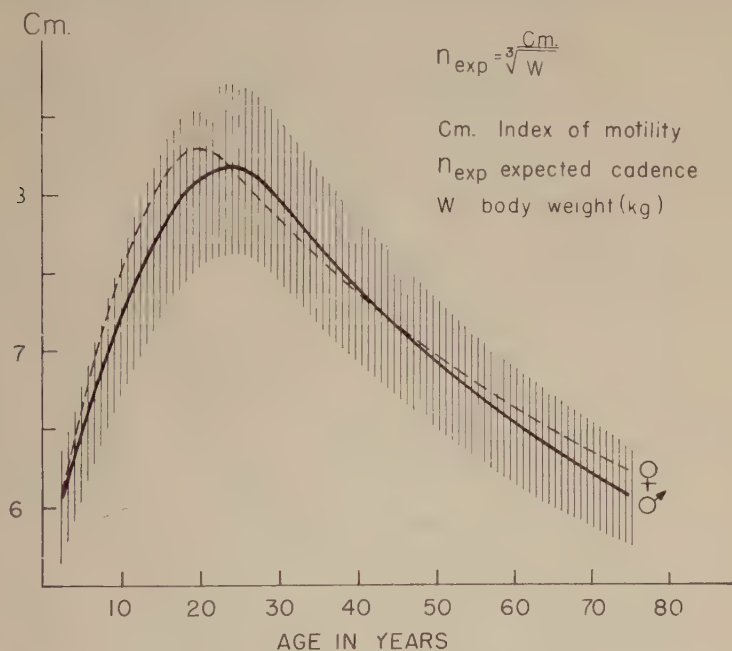


FIGURE 4. Index of motility.

data have been collected for pathological gait, but we can assume that the curve for pathological subjects will be different.

Symmetry of gait. The basic peculiarity of pathological gait is its asymmetry. An observer's subjective judgment of the symmetry of gait is based largely upon his perception of time-interval differences in the sound of sequential footfalls. In normal gait, the rhythm of footfalls is even and the gait symmetrical, since the successive step times are equal and their ratio is one. FIGURE 5 shows that, in pathological gait, the step times are not equal; the ratio differs from one and serves as an indicator of asymmetry. The data shown here are obtained for single individuals, since no temporal studies have been made on larger samples of subjects with a pathological gait.

Ratio of swing-phase time to stance-phase time. Ratio of swing-phase time to stance-phase time is a good indicator of the temporal structure of gait at given cadence. The ratio changes with cadence and, in the case of normal

symmetrical gait, is approximately the same for both legs. In cases of normal gait, this ratio for both legs varies between 0.5 and 0.8. This means that when the ratio is 0.5, the duration of stance-phase time is twice as great as that of swing-phase time. At the point when walking changes over to

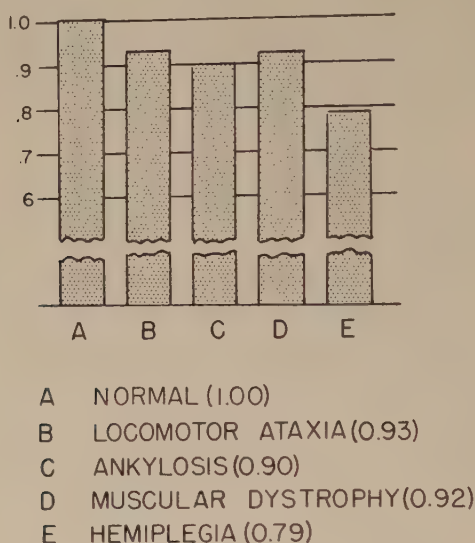


FIGURE 5. Asymmetry of gait.

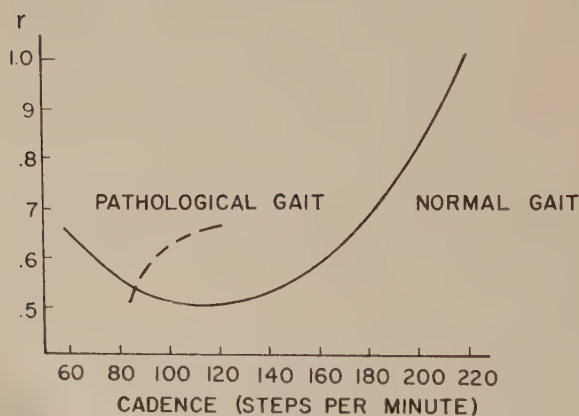


FIGURE 6. Ratio of swing-phase time to stance-phase time.

running, the ratio is equal to one. In pathological gait the ratio is different for each leg and indicates the structural asymmetry of performance at various cadences (FIGURE 6).

Double support time. The double-support time is the time interval during which both legs are in contact with the ground. The investigations of

G. Demeny¹⁴ and our own studies show that in normal gait the double-support time decreases linearly with cadence. The empirical equation of the straight line that graphically presents the observed relationship between double-support time and cadence is computed by the method of least squares. At the maximum cadence when walking goes over into running, double-support time equals zero. In order to predict the cadence at which this would occur, the straight line should be extrapolated until it crosses the base line. It must be pointed out that extrapolation indicates only the possible maximum cadence.

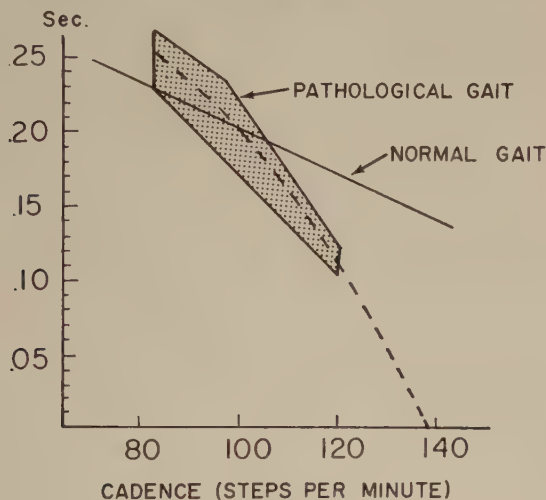


FIGURE 7. Double-support time.

In normal gait the double-support times for both legs are equal, but in pathological gait they are unequal. The decrease of the double-support time intervals with increase of cadence in the pathological gait is not linear, but declines much faster than in normal gait. FIGURE 7 shows how the double-support time changes with increase of cadence for a hemiplegia patient and for a sample of normal subjects.

Variability of step times. Previous investigations of K. Feige²⁴ and others have shown that in walking, as in other repetitive movements, the variability or extent of change of the successive step times is at a minimum at the cadence preferred by the subject, and is his optimum. FIGURE 8 shows that the variability in normals can be as low as one half of 1 per cent. This means that for normal subjects the duration of step times at normal speed is very consistent. At slow and fast speed the step-time variability is much higher. In pathological gait the variability of step times at normal speed is larger than in normal gait, and for slow and fast speed it increases much faster than in normal gait. From the observed variability of step times it seems to be possible to indicate the subjects' optimum cadence.

Kinematics. Steindler⁴⁸ indicated in 1935 that, for a descriptive morphology of pathological gait, kinematic studies are basic. Kinematics con-

siders displacements, velocities, and accelerations of body motions apart from their causes. Since no observer is able to catch all details of human walking pattern, which determines gait, a proper method of objective graphic recording is important. N. Bernstein has established the following requirements for a good recording method of movement: it should provide a proper precision; it should not interfere with or influence in any way the performance of the activity; it should permit an easy interpretation and evaluation of the obtained data.

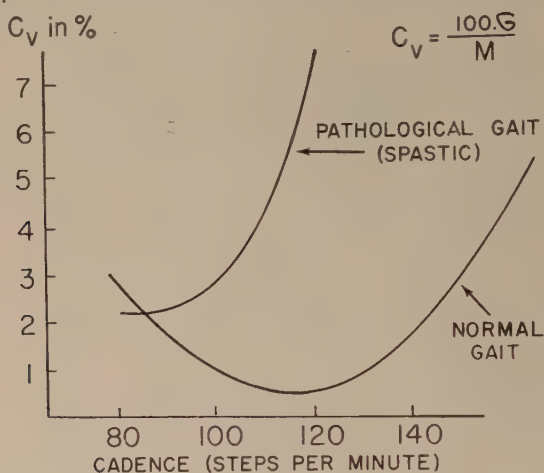


FIGURE 8. Variability of step times.

For a long time the motion-picture method of recording movements was in favor. It is now used less often because the data reduction from successive frames is inexact, difficult, and time-consuming.

At present, for the purpose of gait analysis, the joints and limbs of the subject are marked with a highly reflective tape (Scotchlite) in points and stripes. The subject walks on an instrumented stage erected 22 feet in front of a photographic camera. The camera has a Kodak f/6.3 commercial Ektar lens with a 12.5-inch focal length. DuPont high-speed Panfilm (5 × 7) is used. The camera's light source is a single General Electric narrow-beam RSP-2 500-watt photoflood fixed close to the lens. In front of the lens is a slotted disk driven by a synchronous motor that rotates at 25 rps. The disk has 1 to 4 slots in it so that the reflected light beam from the Scotchlite marker can be interrupted 25, 50, 75, or 100 times/sec. Since the angular width of the slots is 7 degrees, an exposure time of $\frac{1}{1286}$ sec. gives a sharp image of the moving, light-reflecting points and stripes taped to the subject's body. The images show up on the photographic film as "sticks" and are called stick diagrams (FIGURE 9).

This method has an obvious advantage in that it does not influence the performance and, with its time-space relationship recorded on the film, provides a complete pattern of the movement under study. Since measurements of vertical and horizontal displacement and angles on an enlarged print of the

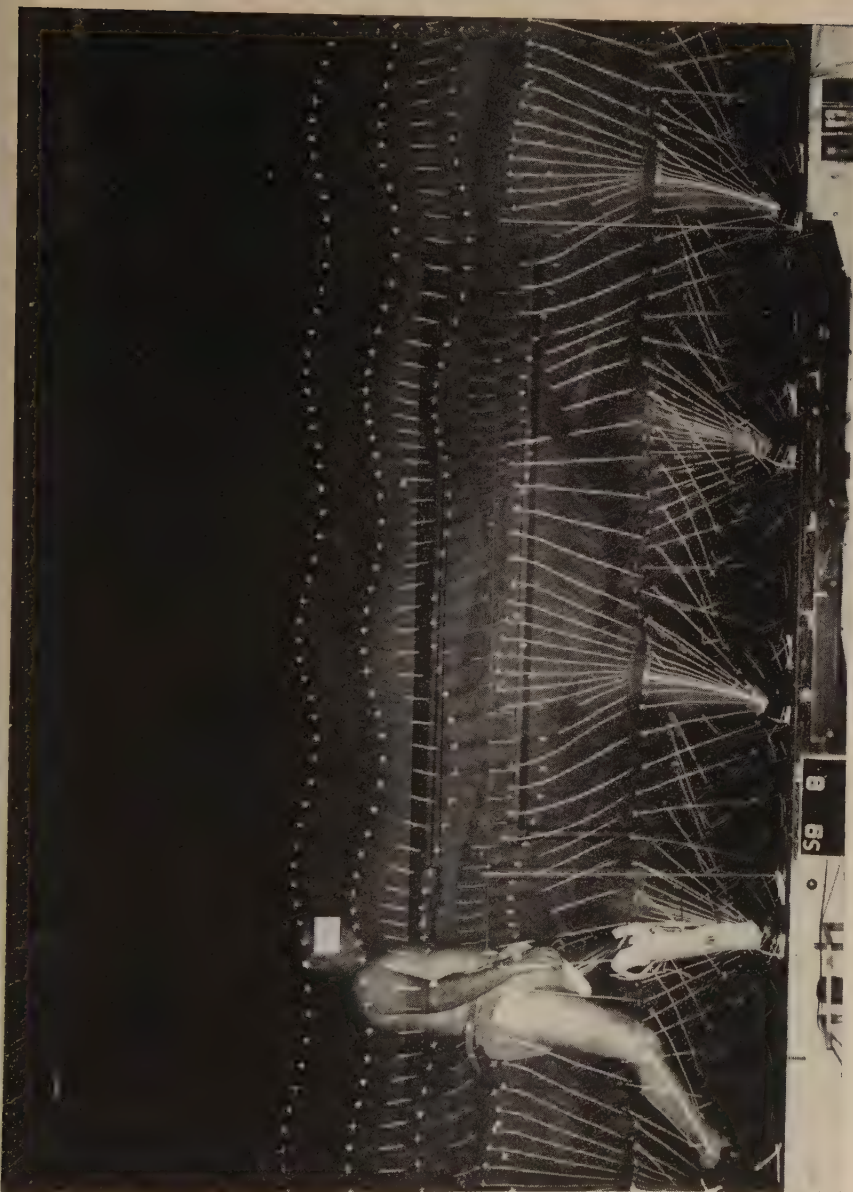


FIGURE 9. Stick diagram of the walking of an amputee.

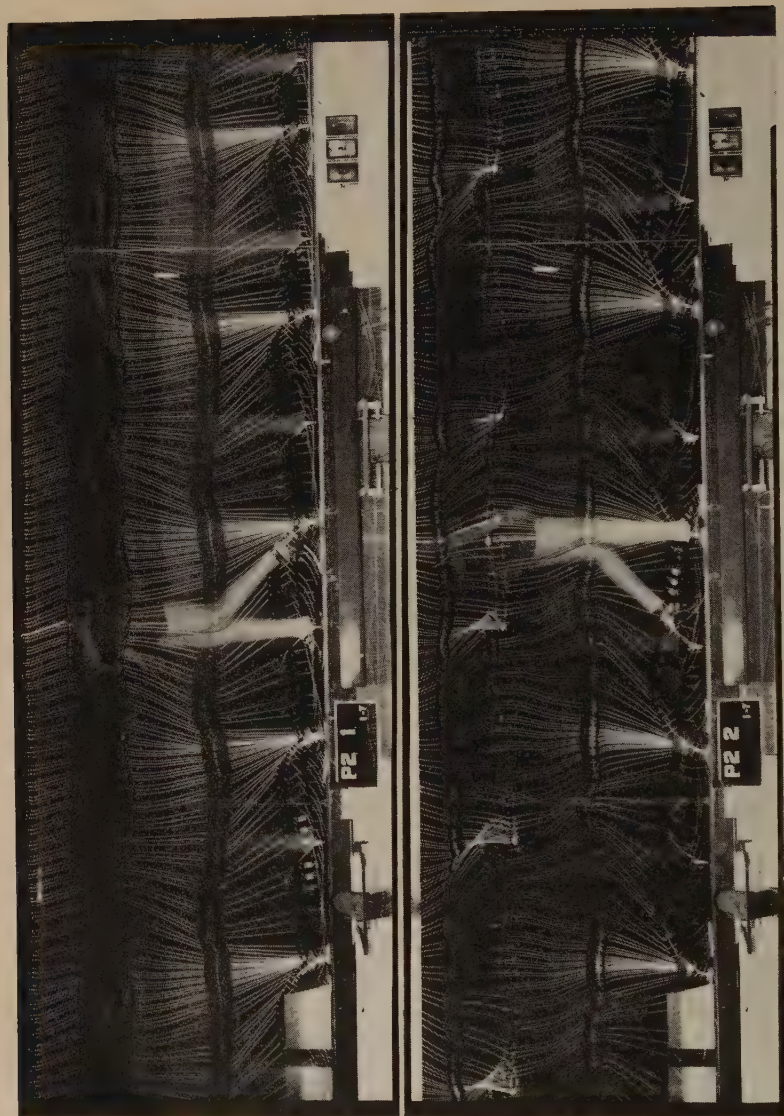


FIGURE 10. Stick diagram of the walking of a hemiplegic patient. The top diagram shows the performance with the paretic leg; the bottom diagram shows the performance with the nonparetic leg.

recorded movement can be made directly from a single set of coordinate axes, the reduction and evaluation of data are greatly simplified. The requirements as set by N. Bernstein by using this method are fully met.

The fundamental nature of body movement during walking is oscillatory in character. In normal gait, the nature of the oscillations is smooth and rhythmic. The pathological gait exhibits less smoothness and consistency in the pattern.

The kinematic analysis of pathological gait from the obtained graphic records can be accomplished by studying the linear and angular displacement of the entire body, the joints (hip, knee, ankle), and segments of the lower extremity (thigh, shank, foot). For the purpose of our investigation, the most important kinematic characteristics of walking are: (1) paths of motion (displacement curves), (2) stride length (limits, range, mean), (3) ratio of stride lengths, (4) speed of walking, and (5) change of instantaneous velocity (as shown by tachograms).

In case the displacement curves should differ significantly, the investigation should be extended, and the linear and angular displacement and velocity of the thigh, knee, and foot should be studied.

A complete description of the technique of kinematic analysis can be found in the New York University Prosthetic Devices Studies Report No. 115.15, *The Functional and Psychological Suitability of an Experimental Hydraulic Prosthesis for the Above-Knee Amputee*, New York, March 1953.

Paths of motion (displacement curves). In walking, displacements of the body and legs occur in a cyclical manner. The successive heel contacts of the same leg are used as the origin and terminal points of each cycle. The distance between these two points is called the stride length. In normal gait the stride lengths are, on the average, equal for both legs; however, the paths of travel of various body and leg points can be quite different for numerically equal stride lengths. In pathological gait the stride lengths usually do differ. By joining the successive positions of the joints on stick diagrams, the displacement curves are obtained. These curves show the paths of motion and the relative positions of the joints and limbs during a cycle of walking. Smooth or erratic movement becomes apparent, as well as differences in patterns of walking at normal and pathological gait. FIGURE 10 shows the stick diagrams and FIGURE 11 the corresponding displacement curves of a hemiplegic patient. It is evident from FIGURE 10 that the step lengths are not equal and that the arm of the paretic side does not swing. The arm swings on the nonparetic side have a changing pattern that is uncommon in normal gait. The displacement curves show that the paretic leg is not fully extended when it comes into contact with the ground, but is set down with heel and sole simultaneously.

The stick diagrams record movement only in a two-dimensional plane. For a thorough biomechanical analysis a three-dimensional analysis is necessary. There are several methods for obtaining three-dimensional recordings of movements. In its simplest form a three-dimensional recording of motion can be accomplished with two still cameras and one interrupter. FIGURE 12 shows our setup for three-dimensional gait photography.

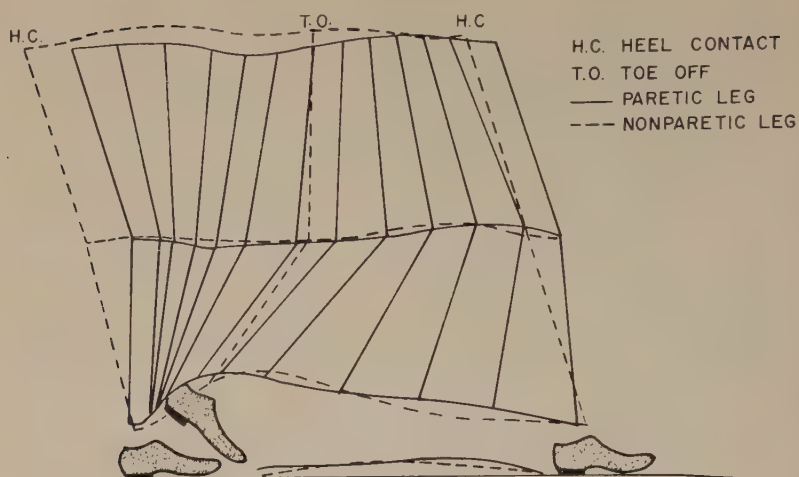


FIGURE 11. Displacement curves of a hemiplegic patient.

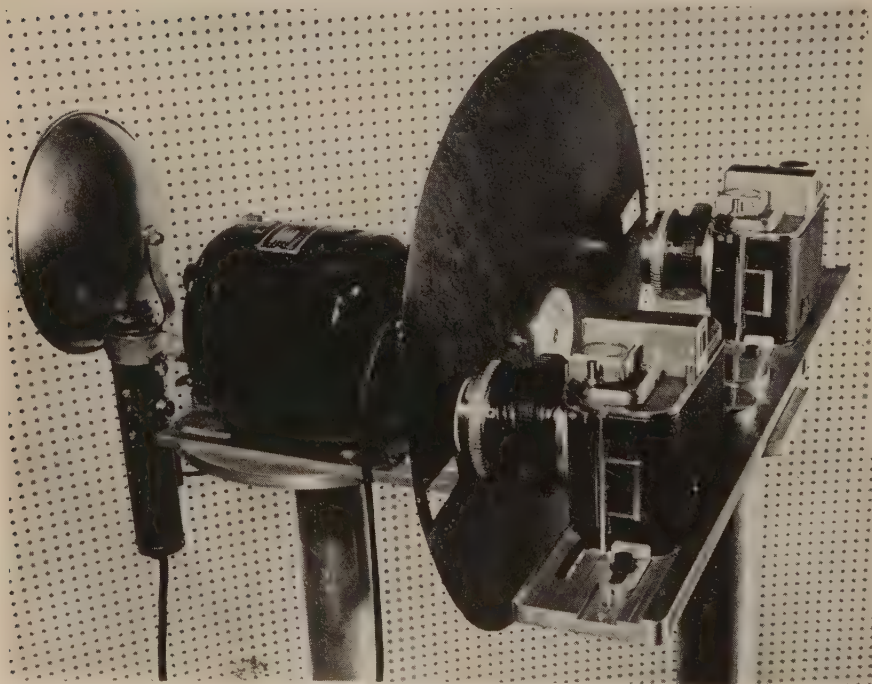


FIGURE 12. Setup for three-dimensional gait photography.

Braune and Fischer⁹ in their investigation used a very complicated method to record the motion in three-dimensional space of the single limbs and trunk of the human body during locomotion. They then calculated the path of the total center of gravity of the human body during a walking cycle. The displacement pattern of the total center of gravity represents the end result of all forces and motions acting upon the subject's body during the walking

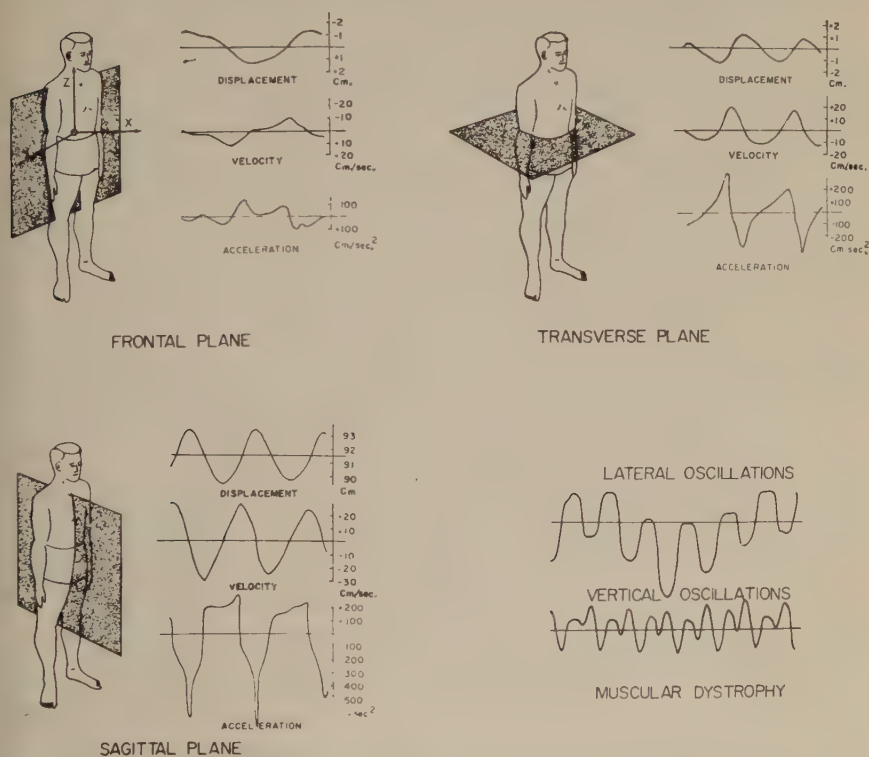


FIGURE 13. Displacements, velocities, and accelerations of the center of gravity of a normal subject during walking, as determined by O. Fischer.

cycle. From the displacements, velocities and accelerations in each of the three reference planes were determined (FIGURE 13). The investigations of N. Bernstein *et al.*⁶ and others indicate that in pathological gait these displacement, velocity, and acceleration curves show definite deviations from the patterns of normal gait.

The sum of the three-displacement curves shows that, in normal level walking, the center of gravity of the subject's body describes an elliptical sinusoid that is stretched in the direction of the progression. An idea of the approximate path of the center of gravity of an above-the-knee amputee can be obtained from the gait-photography picture in FIGURE 14. The path shows a jerkiness that is caused by the particular pattern of the amputee's gait. It



FIGURE 14. Gait photography of an amputee. The top curve shows path of the neck; the middle, path of the center of gravity; and both the lower curves, the paths of heels.

seems that three-dimensional gait photography can provide important information on the deviations of the pathological gait from normal gait.

Stride length. Stride length is the second basic criterion of gait. It is the distance between two sequential heel contacts with the same leg. The limits, range, and mean values are indicators of gait quality, especially when compared against the background of data for normal subjects.

TABLE 2
STRIDE LENGTH OF 936 PEDESTRIANS IN NEW YORK, N. Y.

Stride length	Class limits (inches)	Percentage of total
Very short.....	From 42.0-53.0	10
Short.....	From 53.1-56.5	20
Normal.....	From 56.6-63.0	40
Long.....	From 63.1-67.0	20
Very long.....	From 67.1-78.0	10

The limits of observed stride lengths for the 936 pedestrians are 42 to 78 inches; the range is 36 inches. The arithmetical mean is 60.1 inches, and the standard deviation 3.96 inches. The standard error of the mean is ± 0.13 inches, so that $M = 60.10 \pm 0.13$ inches. The variability of stride length (v) is 6.58%.

In some cases it is more convenient to use a step length that is equal to the

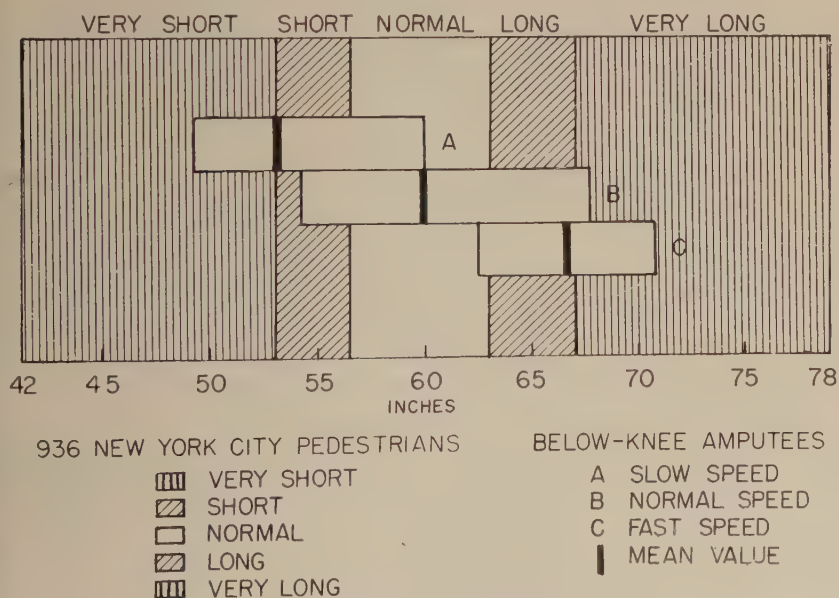


FIGURE 15. Stride length.

distance between two successive heel contacts and, in normal gait, equal to half of the stride length.

FIGURE 15 shows that, due to good prostheses, the small sample (ten subjects) of the below-the-knee amputees was able to duplicate closely the stride lengths of the normal population. In investigation of pathological gait, such comparison of the observed stride length with the stride length of normal populations can be very useful.

Ratio of stride lengths. Experience indicates that, in insecure situations, as in darkness, on ice, or ascending and descending slopes, we tend to take shorter steps. This tendency is accentuated in cases of pathological gait. The ratio of the subject's stride length in situations of this type to his stride length during normal, level walking is related directly to his feelings of security and stability and can serve as an indicator in gait evaluation.

Speed of walking. Speed of walking is the third basic characteristic of gait, and it represents an important criterion for the evaluation of locomotion. The speed is determined from the corresponding step length and cadence values. The limits, range, and mean values should be determined for a sample with a definite pathological gait and compared against the background of the data for normal subjects.

TABLE 3
SPEED OF WALKING OF 936 PEDESTRIANS IN NEW YORK, N. Y.

Speed	Class limits (ft./sec.)	Percentage of total
Very slow.....	From 2.30-3.70	10
Slow.....	From 3.71-4.30	20
Normal.....	From 4.31-5.20	40
Fast.....	From 5.21-5.80	20
Very fast.....	From 5.81-7.20	10

The observed limits are from 2.3 to 7.2 ft./sec. The range is 4.9 ft./sec. The arithmetic mean is 4.76 ft./sec., and the standard deviation $\sigma = 0.58$ ft./sec. The standard error of the mean is ± 0.019 ft./sec., so that $M = 4.76 \pm 0.019$ ft./sec. The variability of the speed of walking (v) is 12.15%.

For a sample of 10 above-knee amputees, the limits of walking speed were from 2.27 to 5.56 ft./sec., the range 3.29 ft./sec., and the arithmetical mean 3.72 ft./sec. It is evident that the lower limits of the amputees and normals are practically equal, but the upper limits differ significantly, as do the arithmetical means.

Change of instantaneous velocity (as shown by tachograms). Tachograms show the velocity variations of the subject's trunk during horizontal forward motion. They provide information on symmetry and smoothness of gait and on acceleration and deceleration of locomotion, and they indicate the individual deviations from the normal pattern. FIGURE 16 shows the tachograms of normal and pathological gait. In normal gait the peak points of the tachograms are coincident with the middle of the double-support time.

The magnitude of the speed deviations from the average speed (marked by zero on our graph) for the sequent steps is close to equality. In pathological gait the peaks are not always coincident with the middle of the double-support time, and the magnitude of deviations for sequent steps is different.

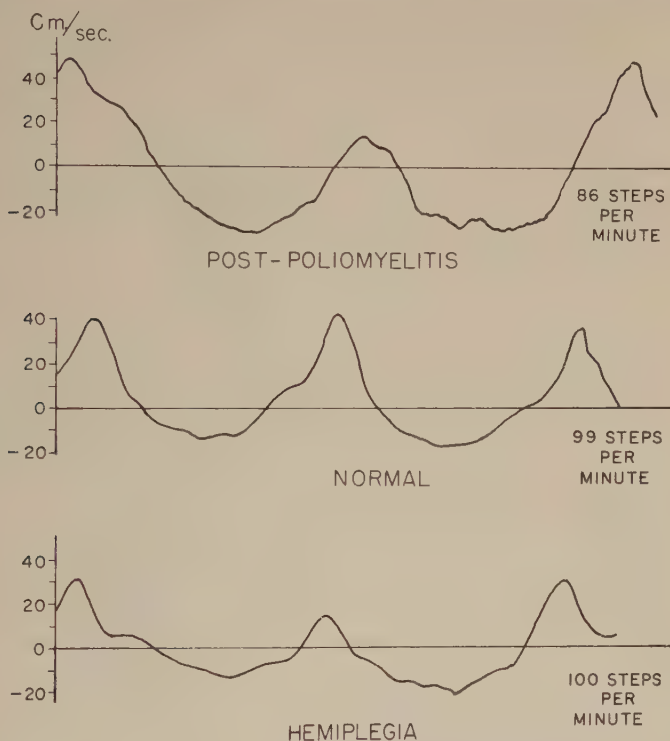


FIGURE 16. Tachograms of normal and pathological gait.

The lowest point of the tachogram corresponds to the moment when one leg is vertical and the other just passes in the middle of the swing phase. The jerkiness indicates the instability of the leg in the stance phase.

Kinetic Factors

Kinetic analysis is concerned with the influence of forces and moments acting on the body during performance of a given activity. Since walking is a very complex process, a kinetic analysis can be very difficult and time-consuming. However, for the purpose of descriptive morphology of pathological gait, it is possible to make some basic comparisons between the magnitudes and patterns of change of the acting forces.

In studying the kinetics of human locomotion, two principal approaches have been used by various investigators. The first deals with the measurement and evaluation of the external forces exerted between the feet and the ground during walking. In order to obtain a continuous record of these

forces, pneumatic, mechanical, and electric methods of recording have been used (FIGURE 17). The second approach deals with investigation of the motion of the center of gravity of the body, the accelerations produced, and the forces acting at this point. In this case the optical or cyclogrammetrical method of recording is used.

The pneumatic method was developed and first used by J. Marey in France. To record changes in vertical reaction forces, special shoes with an air chamber in the sole were used. Carlet¹¹ improved Marey's shoe by using two

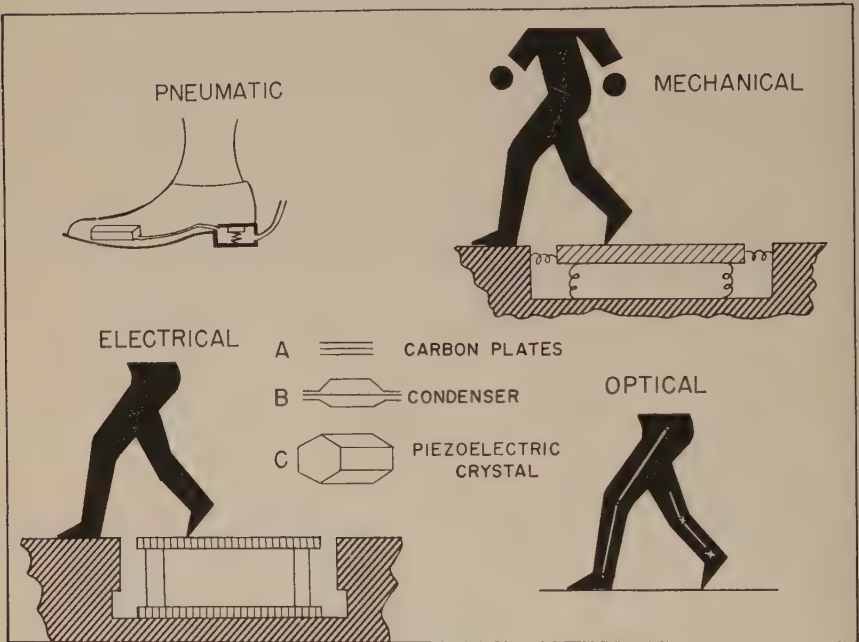


FIGURE 17. Methods for recording forces.

separate air chambers (one under the heel, the other under the middle metatarsal region). In 1932 the pneumatic method was used in the United States by Schwartz and Heath,⁴⁴ who placed air chambers under the heel, the fifth metatarsal, and the big toe.

Several mechanical force-recording methods have been proposed and used. They generally are based on the use of a system of springs and levers. Best known is the dynamigraphic platform of J. Amar,² which gives satisfactory recordings of forces in vertical, lateral, medial, and aft directions. Amar used his platform extensively in the evaluation of artificial limbs and in studies of occupational activities. An improved platform for mechanical recording of the external forces in walking was developed by H. Elftman. It permitted not only the recording of vertical, fore-and-aft, and lateral-medial forces, but also the determination of the location of projection of the center of gravity on the base of support during stance. The attempts of Basler³ and his pupils,

of Rauhut,³⁸ and of Schenk⁴¹ to use a string dynamometer or a mechanical platform with optical recording did not succeed.

Several electric methods have been used for recording forces between the feet and the ground. P. Schwartz fixed columns made up of thin carbon plates under shoes. The resistance of the columns did change proportionally to the vertical forces exerted. A second method—force plates—uses two aluminum plates 15×20 inches each supported at the 4 corners by hollow aluminum columns. A total of 50 specially built electric resistors—strain gauges—are attached to these columns and connected with a recording oscillograph. Each change of acting forces causes a change of resistance and an equivalent change in electric currents in the system. These changes permit an automatic recording of changing vertical, fore-and-aft, and lateral forces, and torques. Similar force plates are built where piezoelectrical crystals convert pressure changes into electric potential changes, which are recorded by the oscillograph (recently, specially built small condensers, made by the Franklin Institute, Philadelphia, Pa., so-called FILPIPS, have been used for measurement of local pressure between foot and ground).

By using the above-mentioned second approach, the scientists, in studying the kinetics of human locomotion, are more concerned with the forces acting at the center of gravity. G. Demy^{14a} was the first person (1887) to try to determine the oscillations of the center of gravity of the human body during walking. This second approach was fully used by Braune and Fischer in their classic investigation on human locomotion, *Walking of Man*.⁹ The same approach was later used by N. Bernstein and his school. Both scientists use the optical or cyclogrametric method for derivation of velocity and acceleration data from photographically fixed displacement cyclograms. The mass and moments of inertia of the body parts involved in motion are determined by using O. Fischer's coefficients¹⁰ or by direct measurement, as described by N. Bernstein *et al.*⁵ For the first approximation, the method of determination of weight and moments of inertia of body parts described by Weinbach^{5b} can be used. These data permit the computation of the magnitude of acting forces and their change. For determination of the accelerations of the subjects center of gravity during walking, I use three electrical accelerometers.

Although the body weight of a subject is a constant value, the magnitude of the forces exerted between feet and ground during stance is variable. Previous investigations have shown that the magnitude of these forces is a function of many factors, the most important of which are body weight of the subject, cadence of walking, time pattern of a stride with its phases of acceleration and deceleration, and position and direction of movement of the center of gravity of the body.

For the purpose of analysis, the actual measured vertical load and the fore-and-aft shear forces are expressed in percentages of the individual's body weight. This eliminates the factor of different individuals and so permits a comparison. For the same reason, the intervals of stance-phase times are subdivided into one hundred parts.

The character of the vertical-load curve can be described by indicating the

location of the peak points (in percentages of stance-phase time) and the magnitude of the maximum load (in percentages of body weight) at heel contact and push-off. These two values determine also the slope of the force curve and thus indicate the rate of change of the force—the “jolt.” Usually the steepness of the force curve for normal gait is greater than that for pathological gait. It indicates that a subject with a pathological gait tends to prolong the time interval from the first heel contact with the ground to the moment when the reaction reaches its maximum. FIGURE 18 shows that in

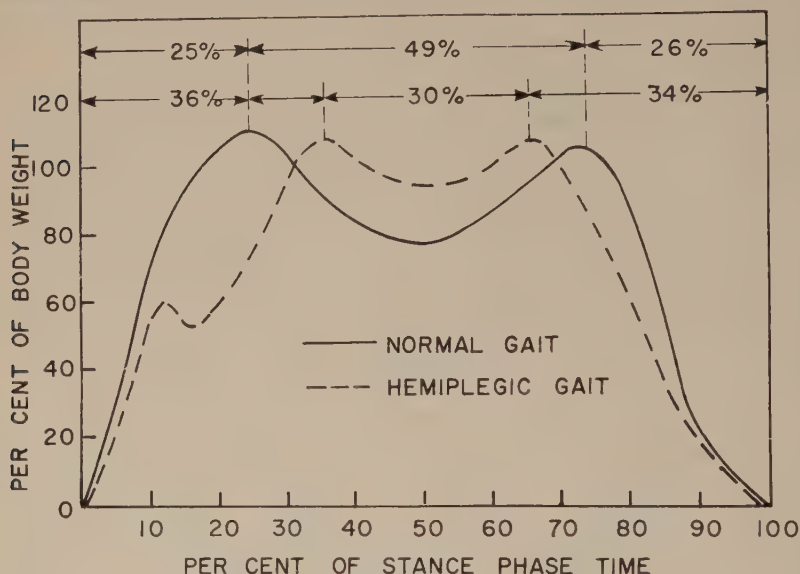


FIGURE 18. Vertical-load curves for level walking, normal speed.

normal gait this time interval is equal to 25 per cent of total stance-phase time, but in the observed gait of a hemiplegia patient it is 36 per cent, that is, significantly longer. The pattern of increase in normal gait is smooth, but in pathological gait is usually “jerky.” The duration between peaks in normal gait is always close to 50 per cent, but in pathological gait it can be as small as 30 per cent. The pattern of push-off phase is similar to the heel contact phase. Again, the force curve of the pathological gait shows less slope stiffness than that of the normal gait and so indicates the subject’s intention to protect his affected leg from sudden force change.

A similar pattern can be observed by studying the fore-and-aft force curves.

An excellent and thorough analysis of the kinematics and kinetics of walking can be found in the studies of Elftman¹⁶⁻²¹ and Bernstein.⁴⁻⁶

The problem of energy expenditure of pathological gait is practically neglected at present. In the future this aspect should receive more attention. The recently started excellent investigations on the metabolism of amputees by Müller^{36a} at the Institute of Work Physiology at Dortmund, Germany, should be mentioned.

Conclusions and Summary

This paper is concerned with the application of objective recording methods to investigation and biomechanical analysis of pathological gait. The main temporal, kinematic, and kinetic criteria are discussed and illustrated. The requirement for comparison of the pathological gait with the normal gait is stressed. The conclusion is that we must collect much more data to be able to establish, in the future, a well-founded classification of pathological gaits.

Acknowledgments

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COMMENTS ON INTERDISCIPLINARY CONTRIBUTIONS IN THE CARE OF THE NEUROMUSCULARLY DISABLED

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To those of us dealing with the broad problems of human disability, the need and value of the special knowledge and talents of the physical, biological, and psychological professions are self-evident. How an effective union of the efforts of many professions may be brought about to benefit the care of the disabled is less clear. In this respect a study of some of the programs providing services for individuals with neuromuscular disturbances may be helpful. Diseases that involve the central nervous and motor systems of the body typify far-reaching disturbances that range from dissolution of integrative functions to mechanical consequences of muscular paralysis or weakness. Clinical experience with these patients and their bedside problems readily demonstrates to us the ramifications and repercussions of such disease processes within most aspects of human behavior. It is in this complexity that the scope of worthy discussion may emerge and a solution appear.

The papers that preceded this discussion illustrated the manner in which the physical, biological, and psychological professions are actively engaged in the solution of specific problems arising in the care and treatment of neuromuscular diseases or injuries. The way in which this type of interprofessional work is facilitated deserves expansion and comment. A synthesis of the experiences of our program will serve as an example to highlight some of the practicalities involved in interprofessional activity. Our experience has been gained from eight years of attention to the care of severely disabled poliomyelitis patients in the oldest respiratory and rehabilitation center, a unit of the program described in detail by Kenneth S. Landauer in the section on Interdisciplinary Research.

Respiratory poliomyelitis is an extreme example of a disease process that involves, directly or indirectly, most of the bodily functions and activities. Clearly identified in this disease situation is the significance of total physical dependence; the interplay between a human's physiological, psychological, and sociological behavior; and the social consequence of prolonging life in the presence of overwhelming disability. It is reasonable to consider the broad implications of the respirator center, because rehabilitation efforts have been possible and worthwhile for these individuals, their families, and society. As various facets of the individual patient's therapeutic requirements and general human needs were recognized, it was possible to assemble during the course of rehabilitation a variety of professional people with appropriate talents and interests in the many aspects of these needs. These specialists had basic science orientation and training in physiology, biophysics, pharma-

cology, and in respiratory, circulatory, endocrine and metabolic investigation, as well as clinical orientation and training in pediatrics, orthopedics, neurology, psychiatry, and internal and physical medicine. Allied professional persons were provided who had training in medical social service, physical and occupational therapy, psychology, chronic-disease nursing, orthotics, and laboratory technology. This was made possible by the broad scope of financial grants-in-aid from the National Foundation for Infantile Paralysis, Inc., New York, N. Y., to the Respiratory Center and the Baylor University College of Medicine, together with provision of adequate payments for the patients' daily care.

The obvious magnitude of the respirator patients' clinical problems has stimulated the bedside collaboration of all personnel. The required comprehensive care and rehabilitation have provided a common goal, resulting in the best possible bedside care from the onset of illness. Comparative experiences with patients admitted late in chronic illness repeatedly emphasize the benefit and importance of the early use of comprehensive preventive and anticipatory measures. In addition to muscular functions, rapidly ensuing physiological deterioration may involve the joint systems of the body, with the production of deforming contractures and fixations. Metabolic disturbances, such as fluid and electrolyte imbalances, disorders of calcium metabolism with the formation of renal calculi, and nutritional bodily wasting can occur. Severe respiratory and circulatory compromises may interfere with the resumption of natural breathing and tolerance of physical activity. Profound emotional disturbances can develop in the patient and in his family. The social repercussions of the disease and the patient's and family's reactions to it can lead to dissolution of the family unit. The daily demands upon the staff include the provision of preventive, anticipatory, and remedial measures for the entire constellation of clinical, medical, psychological, and sociological problems arising in this situation. It is herein that the staff members have come to appreciate their individual, and often collective, inability to do all that should be done, or to know all that must be known. The stimulus to contribute services, to study the reactions of illness, and to enlarge professional knowledge is equally profound and proportionate.

A general evaluation of our experience indicates that the following four particular points of view have evolved and have led to specific programs:

(1) There is fundamental value to simultaneous service, research, and teaching activities, since they stimulate multiprofessional contributions to the solution of immediate clinical problems that cannot be solved by individual effort alone.

(2) The achievement of rehabilitation requires a philosophy, attitudes, and methodology that include: (a) the need for identification of the individual nature of disability as it results from the summation of individual physiological, psychological, and sociological derangements (FIGURE 1), (b) the provision of broad serial description and evaluation of bodily responses from the onset of illness through the rehabilitation process and the identification of their interaction with psychological and sociological behavior, and (c) making available assistance to the disabled person in a way that does not jeopardize his dignity,

DISRUPTION AND COMPROMISE
OF PHYSIOLOGICAL, PSYCHOLOGICAL, AND SOCIOLOGICAL BEHAVIOR

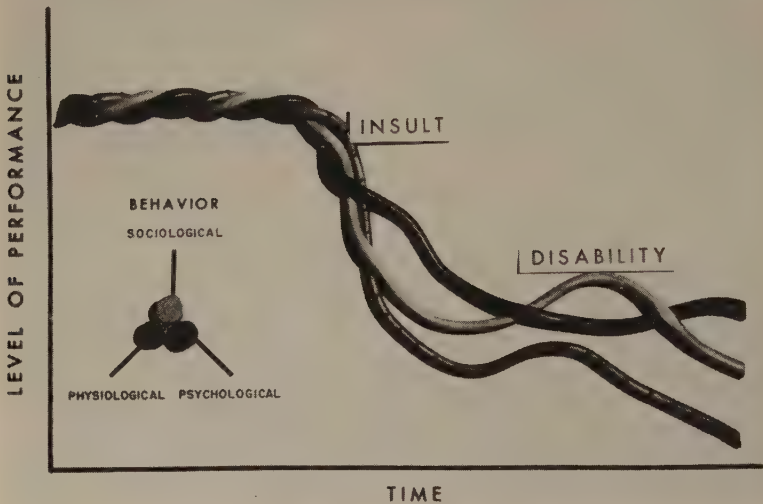


FIGURE 1. The nature of disability is defined by the existence of variable and inter-related degrees of incapacitation, compromise, or loss in three basic areas of human behavior. These areas are considered to exist as one in the collective behavior of man. They are interdependent and may become identifiable in the circumstances of study or during disruptive influences such as illness or the stresses of living.

Physiological behavior consists of the composite activity of the tissues, organs, and systems of the body. These parts of the whole, made up of cellular units, permit and sustain healthy activities of the body. They permit the adjustments to the constantly changing demands upon the body encountered in life. They are capable of adjustment to environmental stresses and strains.

Psychological behavior consists of the composite intellectual and emotional activities and the endowments that identify man as an organism capable of sensing the world about him, of utilizing this information in thought and judgments, and of decision and action.

Sociological behavior consists of the attitudes and patterns of activity that indicate man's relationship to other persons in the world about him. It is taken to include the actions of his family and his reaction to them and his community. It includes his vocational activities and his recreational behavior. It necessarily accepts the reaction of others to his attitudes and actions, since each is assumed to modify the other.

In this simplification, disability results from the summation of deleterious changes in these behaviors. It includes the disruption of the relationship between them and dissolution, compromise, or loss of each of them in varying degrees. By nature, chronic severe disability therefore involves a breakdown of all human behavior patterns under the insult of illness.

self-esteem, or sense of individual integrity. In the latter case, over assistance may stifle the feeble self-sustaining efforts put forth by the patient; in such situations the most realistic hope and motivation may arise from the patient's awareness of any progress leading to independence and the likelihood for resumption of some of the responsibilities of living.

(3) The immediate problems of patient care frequently stimulate research. This appears to define an area of investigation that can proceed most effectively in an atmosphere that combines the research attitude, responsibility for patient care, and the rehabilitation objective.

(4) Teaching is an important part of these endeavors (a) as an aspect of professional growth and development of all personnel and (b) for the effective representation and demonstration of these attitudes to students of medicine, nursing, and the allied professions.

Within the close identification of care and investigatory activities represented in this synthesis of our experience, the research components of our total program arise out of organization *for* research rather than from organized research projects. Research emerges during the course of observation and treatment of the patient. The arrangement for research has been well described by Thomas Rivers:¹

"The scope of medical research in any field has become so broad and the techniques and way of approach to any problem are so varied that one mind cannot adequately encompass them all. Consequently, there must be some kind of organization. Organization for research is just as effective and perhaps more so than is organized, directed research.

"Well educated investigators, free to treat boldly the paths of adventure and discovery are the most important item, but alone can accomplish little at the present time. Well equipped laboratories which include research wards for clinical investigation, ample scientific and technical assistance, and an opportunity and atmosphere for cooperative effort if necessary must be at their disposal. All of this requires organization for but not of research. Therefore, society must see to it that such organization is furnished so that investigators are not forced to spend a considerable part of their time arranging for it."

An orderly and ready documentation of clinical and laboratory experience is a requisite of our pattern of research and concepts. For example, one of the initial developments of the Respiratory Center program has been the provision of instrumentation adapted to the detection, measurement, and recording of physiological events. The system of instrumentation utilized in the respirator center was developed as the vital-studies laboratory, a physiological monitoring system devised by Leslie A. Geddes. This instrument system was designed to detect and quantitate disturbances in respiratory and circulatory functions and energy metabolism during life-threatening complications of acute poliomyelitis, and to program respiratory emancipation and physical-treatment measures in the convalescent patient. A comparable system of instrumentation, the Physiograph (FIGURE 2),² also was devised for the undergraduate and graduate physiology laboratory in the medical college.

The student Physiograph permits easy exploration of physiological events. These phenomena include the nervous, muscular, cardiovascular, and respiratory activities of the experimental animal and the human subject. The system also enables the student personally to explore classic laboratory physiology experiments and to engage in original investigation whenever he is stimulated by his observations. The multichannel recording system consists

of compatible transducers, preamplifying and amplifying equipment, and processing and recording components of modular and interchangeable character. The constant feedback and interchange experienced during daily use provide for progressive improvement and adaptation of the instrumentation according to the requirements of the wide variety of experiments being carried out. The results obtained have proceeded from the early association of

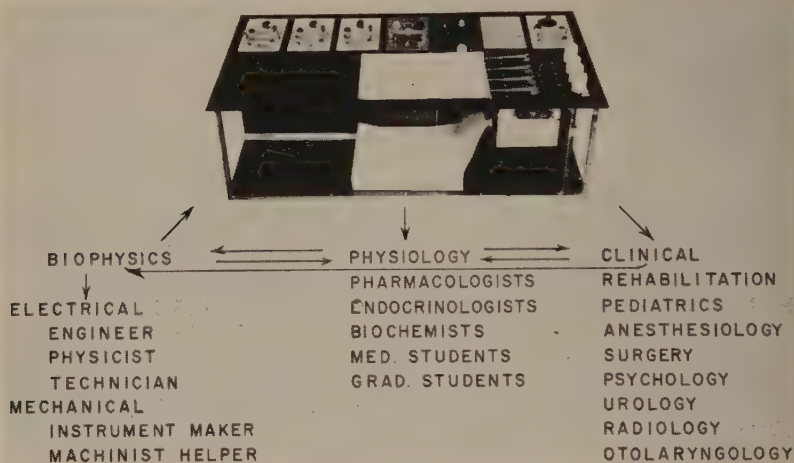


FIGURE 2. Interdisciplinary cooperation in the development and use of the physiograph.* This multichannel physiological monitoring instrument was developed in the Biophysics and Physiology Laboratory, Department of Physiology, Baylor University College of Medicine, in association with the Southwestern Poliomyelitis Respiratory and Rehabilitation Center. The program was engineered by Leslie A. Geddes, an electronic engineer and physiologist, and Hebbel E. Hoff, chairman of the Department of Physiology. The student laboratory model is a successor to a multichannel physiological monitor in the Vital Studies Laboratory at the Respiratory Center developed by Geddes, and is expected to supersede the clinical tool in simplicity, versatility, and adaptability. The various professions and technical skills involved in the development and use of the present instrument program are indicated.

physiology, biophysics, and clinical medicine. This association was fostered by joint activities in investigation in the Respiratory Center, and in teaching and laboratory investigation in the physiology laboratories.

From this example it appears to us that interprofessional activities entwine about mutual or related problems and through common goals in research and education. These activities are like many of our other coordinated efforts in bedside care and in sociological and psychological investigation. We believe they evolve naturally out of the daily experiences of curious people sharing responsibilities for clinical and laboratory problems. Hebbel E. Hoff (personal communication) clearly expressed our general attitude about interdisciplinary activities at the Conference on Teaching Rehabilitation to

* This project was undertaken with the support of Grant No. H-1757 from the National Heart Institute, Public Health Service, Bethesda, Md.

Undergraduate and Graduate Medical Students, at Bandera, Texas, sponsored by the National Foundation for Infantile Paralysis: "We believe that interdependence among the professions grows out of facing a common goal; respect for other persons' competence, judgment and goals is the beginning of teamwork; individual pride is not lessened by group work; the leader in one aspect of a problem need not necessarily be the leader in another."

Two requirements stand out in the achievement of interdisciplinary contributions in the care of the disabled. First, it is essential that there be adequate financial support of the program, adequate facilities, and competent full-time personnel in order that exemplary service may be provided to the patient. Second, the dedicated assistance required of the staff must be motivated and perpetuated. If this can be accomplished, we believe productive research and teaching emerge to the benefit of the patient as the center of all activities. Improvement of individual professions follows as a product of simultaneous service, teaching, and research activities.

A variety of provisions must be recognized and incorporated in order to realize the full potential of interdisciplinary contributions. This begins with the acceptance of the proper area of interprofessional functioning. It is our belief that the arena of major problems of medicine and of science that exceed the capability and sufficiency of individual efforts is such an area. The complexity and extensiveness of the problem itself dictate the need for such activities. Generally, these interprofessional contributions are insufficient if provided solely by consultation. Real joint participation arising out of common interest is essential in the solution of problems. Successful contributions of time and effort derive from a perceived urgent need and personal interest in some part of the problem dealt with.

The opportunistic research extending out of daily experience must be pursued readily or it will be wasted. The long administrative process of obtaining financial support and facilities must be by-passed. In addition, the rate of accumulation of experimental experience in this broad approach to research must be increased through modern instrumentation. Along with this there must be large increases in the automation of data reduction, analysis, and computation to retrieve time for the design and practice of procedures of inquiry.

Finally, self-sustaining reactions must be developed through educational recruitment of superior personnel if interdisciplinary activity is to be fostered. Students must be taught in an atmosphere that demonstrates the proper place and value of interdisciplinary programs. New measures of productivity in these endeavors must be recognized by the participants and the supporters of these programs. These new measures should include service accomplishments, rapidity and effectiveness of growth, and communication of knowledge and techniques to others working in the field. The contributions of the many individuals required for a particular investigation and the rapid diffusion of their ideas, promoted by joint activities, may not be fully acknowledged in conventional publications designed to establish the merit of a particular investigator.

In conclusion, interdisciplinary contributions in care, teaching, and research

are a necessary part of the process of comprehensive assistance to the disabled because of the complex nature of disability. The whole of any united effort for the betterment of the disabled or the development of scientific and technical knowledge for the improvement of mankind is the goal to be kept in mind. The techniques of procuring such contributions require much experimentation and large financial support. The general motivation for interprofessional union of effort may be found in the humanitarian importance of assistance to the disabled. The sensibility and the acceptance of human responsibility are professional and social attributes that form a bulwark of our democratic culture. The provision of optimal assistance to all of those who are disabled deserves particular emphasis in the scale of values of our society and in our professions.

Acknowledgments

I express my appreciation to Hebbel E. Hoff, and Leslie A. Geddes, of the Department of Physiology, Baylor University College of Medicine, and to my associates in the Respiratory Center program, Carlos Vallbona, Robert R. Jackson, Gunyon M. Harrison, and Paul R. Harrington, whose contributions, thoughts, and comments are liberally incorporated in this paper.

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CONTRIBUTIONS OF THE PHYSICAL SCIENCES TO PROBLEMS OF NEUROMUSCULAR DYSFUNCTION

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The physical scientist can make a broader contribution to the problem of the disabled human with neuromuscular dysfunction than may have been inferred from the paper by Drillis, elsewhere in Part III. Gait studies and biomechanical analyses of locomotion constitute but one area of endeavor.

First, the physical scientist is the prime mover in fundamental studies of upper extremity activities. Such studies are, like gait analyses, based on temporal factors, as in time study; on the kinematics, as in motion study; and on the kinetics of muscle and motion. Upper extremity functional limitation constitutes a more severe vocational rehabilitation problem since activities of the arm, forearm, and hand are still major essentials in most occupations. Therefore, it might be preferable for the physical scientist's efforts to be directed at this area, at least at first.

Second, the physical scientist applies the findings of studies on all body parts to construction or reconstruction to compensate for the human disability. However, such application must be tempered with a knowledge of human limitations, desires, and motivations, as well as an appreciation of the greater variability encountered in biology than in the physical sciences, particularly in the applied physical science of engineering.

Fundamental and evaluation studies of *locomotion* have been conducted in the last decade at the University of California, Berkeley, Calif., and at New York University, New York, N. Y., primarily as part of the Artificial Limb Research Program supported by the Veterans Administration and by The National Foundation for Infantile Paralysis, Inc., New York, N. Y.¹ Comparable *motion studies* on the upper extremity have been made at the University of California at Los Angeles.² The studies at these institutions have greatly increased knowledge of forces and motions involved in common human activities and have led to a rational basis for assigning priority to the various possible motions. For example, in the upper extremity, prehension is most important. Elbow flexion and the possibility of stabilization of the elbow in any of a reasonable number of positions are next in importance, but passive adjustment of pronation and supination would often be adequate when voluntary control is impracticable. Wrist flexion was shown to be of very low priority, and a few positions of passive adjustment, if provided at all, are entirely adequate.

These principles and somewhat comparable information on the lower extremity can guide in the selection of joints for braces and the use of an extremely limited number of auxiliary power sources from other parts of the body. Studies of the energy required and the role of the various joints in walking also provide a basis for long-term analysis of the importance of locks, counterweighting springs, or voluntary control of the various joints. These

results of research, as well as humane and economic factors, should guide consideration at any given stage of recovery of the relative importance of surgical stabilization, muscle transplant operations, or bracing.

Studies of muscle activities at both campuses of the University of California¹⁻³ have emphasized electromyographic measurement of muscle activity and have shown the importance of the force-length curve originally described by Blix⁴ and its implications in connection with the importance of preventing contractures and of reducing the steepness of the "passive stretch curve" so as to increase the forces voluntarily available in connection with muscle and tendon transplants and tendon lengthening. A whole field of bioengineering development is available in the application of this type of quantitative information to the problems prevalent in neuromuscular dysfunction.

The Veterans Administration also has conducted a limited amount of research in its own facilities. At first this research was directed at general lower extremity-bracing problems. In 1952 a survey of veterans wearing leg braces was conducted to elicit reactions to appliances then being worn.⁵ Findings of this study showed the following common reactions: (1) a desire for lighter, less bulky appliances; (2) complaints of clothing damage, lubrication staining, and tearing in the joint regions; (3) complaints of wear of joints and consequent noise and the gradual loss of stability that occurred because of such wear; (4) complaints of breakage; and (5) complaints of inconvenience caused by the need for frequent repair.

As a result of this survey, subsequent development and evaluation, as performed by the Veterans Administration working in concert with manufacturers, was directed at these particular complaints.⁶ A reasonable amount of progress has been made in correcting and modifying the component design of the lower extremity brace and brace-making methods to reduce the severity of the problems that have traditionally plagued the brace wearer.⁷ Solution of these obvious surface problems, with the help of teams for prescription, check-out, and follow-up, should now permit attack on the basic problems of energy, control, and sensory feed-back, problems so inherent yet apparently insolvable that patients dare not even name them.

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Part IV. Sensory Dysfunction

ENGINEERING RESEARCH ON PROBLEMS RESULTING FROM SENSORY LOSS

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Introduction

Although the need and value of the application of engineering effort to problems resulting from sensory loss have been apparent for a long time, relatively little has been done in this area until recently. It is true that very significant contributions were made before 1940, and that the earlier work has been the basis of much of the progress achieved since, but relatively little money has been available and most qualified people have not been aware that they could contribute to the solution of these problems.

It is gratifying to realize that the engineer is now finding support and challenge in the field of sensory loss—and to observe the mounting volume of his contributions. The engineer's work has been most keenly felt in the problems of impaired hearing and vision, and it is with these (especially the latter) that I propose to deal.

We are all familiar, for example, with the amplifiers that have been developed to assist the hard-of-hearing. Even the early ear trumpets represented an application of known principles of acoustics, and these trumpets, despite their awkwardness, served a very useful purpose. Since the days of the first vacuum-tube amplifiers, thought has been given to the development of electronic hearing aids, and it is certain that, as hearing aids have improved, the population has become more willing to use these devices, thus encouraging even greater strides. Consider the matter of size; many of us may find it difficult to understand the reasons for making hearing aids still smaller than the already compact modern units. Whether the hearing-aid engineers caused or followed the miniaturization trend is hard to say. Perhaps they will next bend their skills toward improved quality, extended battery life, and to a possible solution to the problems associated with nerve deafness. Present hearing aids do not do as much as is desirable for an individual whose hearing loss is due to nerve degeneration. While additional power may help some people, this increased volume applied to the eardrum does not produce a corresponding increase in, for instance, the intelligibility of speech sounds. There are some new ideas on hearing aids, such as the magnetic method for driving the eardrum. Since a number of competent groups are devoting considerable attention to problems of hearing, it would be surprising if their labors did not point the way to improved engineering devices in the not too distant future.

Engineering directed toward problems resulting from loss of visual acuity is less well known.

The way to help those with diminished acuity in any sense is more apparent than the way to help those with complete loss of function. The usual hearing aid is a device intended for the hard-of-hearing and affords no help to the totally deaf. Those who cannot hear at all depend upon lip reading or, in the case of the deaf-blind, upon tactile listening. A number of attempts have been made to present speech in visible form for the totally deaf, but none of these, so far as I know, is now very widely used.

For the partially sighted the answer is magnification and, perhaps, increased contrast. For the totally blind the solutions must be much more radical and present very challenging engineering problems.

The Blind

Problems resulting from loss of vision may be grouped in several categories that are convenient for the engineer. One of these is guidance. The functions a device may perform are related to obstacle detection, step-down detection, and general orientation. By obstacle detection, of course, I refer to means that will help a blind person know when he should stop to avoid collision with a stationary or moving obstacle. By step-down detection I mean apparatus that will give warning of approach to a down curb, or an open cellar way, a flight of stairs, a ditch, or open manhole. By general orientation cues I mean the kind of information that will enable him to select an efficient path through a maze, that is, to enable him to walk across a room and around a table without tracing a path like a billiard ball bouncing from one cushion to another. The blind person would like to "see" further than the end of his nose or his cane.

There are many problems in communication that are unique to the blind. Without sight, one cannot read the printed material available to the rest of us. Recently a great deal of effort has been devoted to devising methods of converting ordinary print into forms intelligible to the blind.

Most of us are familiar with the talking book and variations of this scheme. The problems involved are quite similar to those that occur in the development of other sound-recording systems, but the requirements are not exactly the same. While, of course, no one today would dare to profess a lack of interest in high fidelity, the talking-book program is still burdened with problems of price, of weight of the records to be shipped, of the number of times the records can be played before becoming unacceptable, and the abuse to which listeners may subject them.

Braille itself has been greatly improved since it was originated in 1829 by Louis Braille, but it also presents many challenges to those working in the field. The development of adequate paper stocks and of printing and binding techniques are of major importance to the persons responsible for turning out literature in this medium. Although Braille is highly satisfactory for many of the blind, only a small proportion ever learn to read with any degree of facility.

The Partially Sighted

There are, of course, many persons whose reduced visual acuity makes it difficult for them to perform many of the tasks that normally sighted people

take for granted. For reading they will first try to get the best refractive correction. If ordinary spectacles still do not make satisfactory reading possible, additional magnification can be obtained through the use of special spectacles such as telescopic lenses; some very excellent new designs have recently been disclosed by W. Feinbloom and J. C. Neill. During the war there was a concerted effort to develop improved magnifying lenses suitable for binocular use, and H. Jehle, at Harvard, developed a projection magnifier. Subsequently this was improved at The Franklin Institute, and further improvements were made by a group including W. E. Frank, H. P. Schick, and G. J. Kreier, Jr., which led to the present commercial versions of the device. Another projection magnifier is marketed through the American Foundation for the Blind, New York, N. Y., to serve the needs of those who require even more magnification.

Contact lenses have been improved greatly in recent years, and these frequently permit those with loss of acuity to read at relatively high efficiency. In addition, those whose corneas have been replaced by plastic substitutes appear to be doing well, and the development of artificial corneas continues as a cooperative effort between the surgeon and the engineer.

Reading Problems of the Blind

Converting printed material into speech. Almost all of the uninitiated and most of the initiated think that the ideal solution to the reading problem is a device that will convert printed material into ordinary spoken language. This conversion does have the tremendous advantage of being easy to use because it is so designed that some miracle of modern engineering, or a sighted reader, does all the learning, while the listener merely receives the information in a form to which he has been accustomed throughout his life.

The fact that such conversion is difficult is not the reason for its shortcomings as a complete solution. Spoken language is a relatively slow means of communication compared to visual reading and even compared to tactile reading by a competent reader. There is need for a better means of converting the printed material available to sighted people into a form intelligible to the blind. Certainly spoken language would be a great help and, for many, would be the best form. A modification of ordinary speech, perhaps compressed speech, might be still better, thus creating nothing new to be learned, but making possible a much higher reading rate.

It is not really the responsibility of the engineer to suggest the most suitable system, although any one who has thought about the problem undoubtedly will have formed some idea about the form the output should take. The final decision is a problem for the educator and the psychologist. In considering reading-machine outputs, as in considering all other aspects of sensory aids, it must be borne in mind that there are many different requirements that depend upon the individual, his background, intelligence, aptitude, and needs in the particular instance under consideration. There is no universal solution, and any single solution is a compromise bound to be unsatisfactory in many instances.

In trying to progress in this field, the Committee on Sensory Devices of the

National Research Council Washington, D. C., contracted for the development of two reading machines by the Radio Corporation of America (RCA), New York, N. Y., shortly after World War II. One of these, developed by V. Zworykin and W. Pike for RCA, converted printed material into a spoken letter presentation: thus the word car would be presented "C" "A" "R." The machine had a limited vocabulary and, when it recognized a word, it presented it as a word instead of pronouncing each separate letter. The second reading device did not have within it the means for recognizing the letters scanned. This function was reserved for the brain of the user. The machine presented a tone signal of varying pitch that an experienced reader could recognize in terms of the letters that had been scanned. The reading head was drawn by hand across the line of type, while an internal optical system performed a high-frequency vertical scan. This machine was the basis for an evaluation program carried out at the University of Michigan, Ann Arbor, Mich., to determine the feasibility of the method.

For some time after the construction of these machines, very little work was done. Then the Veterans Administration (VA), Washington, D. C., and others became interested in the problem again, and a series of reading-machine conferences were held under VA auspices. In these meetings, psychologists, speech experts, representatives of firms interested in the commercial aspects of letter-recognition machines, and others met to discuss the problems and the most likely methods of solution.¹ The consensus seems to have been that recognition machines probably will be too expensive to be owned by each blind person, but that home readers without recognition functions, containing much less mechanism and circuitry, could be of great value in reading personal correspondence and other limited reading.

As a result of these studies, the VA is now sponsoring a limited research program in the field. It seems that, given sufficient money, the technical problems of letter-recognition-type machines could be solved, since the principles have been well established in many commercial devices. The most difficult problem is the development of suitable output. Both the Bell Telephone Laboratories and the Haskins Laboratories, New York, N. Y., have done a great deal of work in speech analysis and synthesis, and H. Dudley of Bell Laboratories and F. S. Cooper of Haskins Laboratories have made valuable suggestions concerning the feasibility of making it possible for such a device to present its output in synthetic speech. The computer experts suggested that with present memory devices it may be feasible to have the machine utter good spoken English from an auditory dictionary previously recorded on a storage drum. The home-reading-type machine appears to be rather limited in flexibility and, while changes in the details of scan and output have been considered, past experience indicates a serious learning problem in the mastery of this technique.

In connection with the reading-machine problem, it should be remembered that as early as 1913 D'Albe² developed the reading optophone, a device that used photocells to convert printed letters into a tone pattern; it was alleged by the supporters of the development that at least one experienced reader was able to achieve a reading speed of 60 words per minute. In method of

operation, the optophone worked much like the A2 reader developed by V. Zworykin and L. Flory and now being improved. The recognition machines utilize logical circuits not generally known in those days.

Raised-dot reading. Braille has been revised many times and is the subject of a continuous research effort. The American Printing House for the Blind, Louisville, Ky., for instance, at its annual meeting there every spring brings together many of those interested in Braille publication to discuss technical problems pertinent to their work. With the support of the Library of Congress, Washington, D. C., they have just completed a new investigation of the effects of dot size and spacing upon reading speed, intelligibility, and learnability. This was primarily a psychological problem, but it is reflected in the engineering requirements of the Braille printing devices.

The American Printing House for the Blind also has recently installed automatic controls for the stereotype machines that emboss the plates from which the Braille is printed. This development, carried out in cooperation with the International Business Machines Corporation, New York, N. Y., uses a punch-tape control and a typical IBM verifying system for proofing. Under the old system, error corrections were rather difficult and required a high degree of skill, since the plate had to be flattened and then repunched by hand around the error. We can look forward to the day when the tapes are prepared, by operators not familiar with Braille, in ordinary type English, and the abbreviations and contractions are taken care of automatically by a computer mechanism.

The Braille presses constantly are seeking paper stocks that can be embossed more satisfactorily. Good embossing, depending upon stock as well as press, results in a clear dot, with no break in the paper at the top of the dot, since sharp paper edges soon irritate the fingers of the reader. It is also important that the Braille withstand many readings without obliteration. One serious problem in Braille reproduction is the manufacture of limited-number runs; the plastic printing plates may have solved this problem. We do know that a number of special processes have been developed, one in Philadelphia, Pa., by the Volunteer Services for the Blind, which makes possible the practical reproduction of a very limited number of copies from the Braille master.

Some time ago J. N. Wheeler of IBM devised a machine that produced Braille on a moving tape from a punched-tape master. This device used a very inexpensive, compact, and easily reproduced method of storage for Braille. There are some problems connected with the machine itself, but this is to be expected of any new development. A related device suggested by G. H. Zuk uses a punched-paper master of the same size as the final Braille copy.

Murphy and Friedrich of the Veterans Administration have done some work on the direct utilization of the teletype setter tapes used to control many printing processes. Friedrich has built a device that converts this code into Braille. While the Braille is, of course, Grade 1, that is, without contractions, nevertheless this system offers hope of making available, to those blind who read Braille, material prepared for printing by conventional means.

Naturally the same equipment could be used for any other letter-by-letter output.

We at The Franklin Institute³ have been concerned about the fact that so few of the blind, particularly those who lose their sight later in life, become proficient Braille readers. There is a good library of material available in Braille for those who can use this form, and it was our feeling that perhaps a significant number of individuals could learn a tone-code system directly related to Braille. Conversion can be accomplished with very inexpensive apparatus, and tonal Braille might serve not only as a reading system by itself, but as a method of teaching ordinary Braille. Initial experiments have been inconclusive.

No discussion of the problem of tactile reading is complete without consideration of the many schemes devised to convert printed material into an embossed and perhaps enlarged copy. One of the most successful of these devices was the Visagraph, developed in 1930 by R. E. Naumburg. The Visagraph embossed aluminum foil to make a raised copy of printed material. It could be used for printed letters as well as diagrams and pictures. More recently others have proposed transient raised-dot copying of printed material. These devices generally have an arrangement of movable pins that may or may not be elevated, depending upon whether the corresponding part of the material scanned is inked.

All of these experiments have led to much frustration. There is little doubt that simple graphs and line drawings may be presented best in this form. The unfortunate fact, which no one has yet circumvented, is that type styles that are easily read with the eye are most unsatisfactory for tactile reading. Despite the fact that the individual may be thoroughly familiar with the general shape of letters, it is quite difficult to recognize individual characters. A comparison between the simplicity of Braille and the relative complexity of ordinary letters illustrates how poorly conventional type faces meet the requirements of Braille, the best system thus far devised for tactile reading.

Guidance Devices for the Blind

Much has been done in the field of guidance devices for the blind.^{4, 5} As early as 1912, D'Albe demonstrated the exploring optophone, a light-finding device for locating objects such as windows and doorways. Some of the work goes back to the Committee on Sensory Devices. Under this committee's program, which was coordinated at the Haskins Laboratories, a number of different radiations were used in the development of obstacle detectors for the blind. These included ultrasonics, visible light, and ultraviolet light. Other inventors have used radar and radio-frequency methods. Some devices developed here⁶⁻⁸ and in England used audible sound.⁹ The guidance devices using ultrasonics had in them circuits that measured the time required for the sound to travel from the transceiver to the obstacle and return. One of these devices was developed by the Brush Development Company, Cleveland, Ohio, another by the Hoover Company, North Canton, Ohio, and still another version by the Stromberg-Carlson Company, New York, N. Y. There were

problems due to air turbulence and to reflection from smooth, plane surfaces at an angle to the beam. Also, a step-down was not detectable.

At about the same time a visible-light guidance device was developed by L. M. Cranberg at the Evans Signal Laboratory, Belmar, N.J. This device was an optical range finder using a rotating coding disk which intercepted the beam to produce a signal whose frequency indicated the distance to the obstacle.

The information given by this Signal Corps device was the distance that the very narrow beam of light (3-inch diameter) traveled until it hit an obstacle. The individual who used the device had to do the scanning. This device was built in pilot quantity, with additional engineering by RCA. Units were evaluated at Haverford College, Haverford, Pa., under T. A. Benham, who found many advantages for this kind of guidance instrument, but concluded that further development was necessary to eliminate certain objectionable mechanical features. While the device can be used for step-down detection, it is not well suited to the performance of both functions by the average operator.

Before the Signal Corps device was re-engineered, R. E. Benn suggested, and then W. E. Frank and F. F. Ohntrup at The Franklin Institute developed, an optical ranging device using ultraviolet light. It was intended that the shorter wave-length radiation, shorter than that present in the atmosphere, would suffer less from specular reflection, and that the device would be affected less by noise. From an engineering point of view, the device represented a very interesting advance, but the amount of improvement in the optical ranging system measured against additional work done by RCA did not seem to justify continuation of the development of the system. The basic question was one of the adequacy of the data from an optical probe, not "what is the ideal wave length of the radiation?"

The British government conducted some research on a guidance device for the blind immediately after World War II, but evidently this work terminated much sooner than the work being done here. One item of particular interest developed by the British was a clicker that emitted bursts of audible sound at a regular rate. The sound source was electromechanical and was housed in a flashlightlike device with a reflector in the front. The user simply points the clicker in the direction he wishes to investigate and listens for the echo. Using such a device, a skilled operator can tell much about the obstacles ahead. A main difficulty, of course, is that no provision is made for warning of step-downs.

Another group of investigators has concentrated on devices that utilize an ordinary cane as an essential part of the guidance device. Richardt and Shann¹⁴ of the Bell Telephone Laboratories patented a cane with a built-in ultrasonic detector that was energized by leaning on the cane. Thus, obstacle location was extended well beyond the cane tip. At The Franklin Institute, Frank and Ohntrup started work some years ago on what we have called a "sensitive cane."^{15, 16} The original models provided both obstacle and curb detection, but it soon became apparent to us that there were serious problems involved in discriminating between the two danger signals. Therefore we

have concentrated on curb detection by electronic means. The philosophy behind this approach is that the cane, a physical extension of oneself, gives confidence and, should any of the electronic circuits fail, the user can still proceed, perhaps more slowly, but nevertheless safely. More recently, J. E. Berry, in Van Nuys, Calif., and M. A. McCollum in Kansas City, Mo., have been working on similar devices. All of these devices are, of course, under constant test.

A most interesting guidance device for the blind has been built by Kallmann.¹² The unit, which he calls Optar, uses ambient light, although it can be used with a flashlight at night. It measures the distance to the nearest obstacle at which it is pointed by locating the plane of the image of the obstacle within the device. A coding disk then gives a signal whose pitch is related to the distance.

While the sensitive canes were designed specifically to solve the problem of step-down detection, more sophisticated techniques for step-down detection also have been tried. We were not too successful, but Witcher at the Massachusetts Institute of Technology, Cambridge, Mass., and, more recently, Benham¹³ at Haverford College, and J. M. Benjamin at Biophysical Instrument Company, Philadelphia, Pa., have been encouraged by their progress on optical devices for detecting step-downs. These devices work on the principle of finding a discontinuity in the distance from the detector to the ground as the beam is scanned automatically. A principal design problem lies in the development of a unit that will work reliably even though not held at a constant distance from or at a constant angle to the ground. If the device is to be carried by a blind person with normal gait, obviously it will be subject to considerable motion in space as the person walks.

Other Devices for the Blind

The American Foundation for the Blind has a whole catalogue of devices designed or selected to make work easier for the blind. These devices have been catalogued under the direction of C. G. Ritter. Typical of these are such well-known devices as Braille watches and a pressure cooker with an audible pressure indicator designed for the general population, but of especial help to the blind cook. There are devices to aid in such occupations as drawing, machine tool work, carpentry, sewing, and measuring temperature. Many blind individuals have themselves developed devices that serve particular ends. For instance, many electronic specialists have constructed instruments that substitute for the meters used by the normally sighted engineer.

Rehabilitation

No doubt much has been done in isolated plants to increase the employment of those with sensory handicaps, but little has been published on the subject. As yet, there is no real armamentarium of devices. Currently we are working with the Commonwealth of Pennsylvania on a project designed to improve the employment opportunities of a specific class of the visually handicapped. In the past we have made special devices that have enabled blind people to perform functions they could not otherwise undertake.

Witcher^{10, 11} has devised a universal optical locator for the blind that can be used to read dials or simple numbers; Benham has described an aural current indicator. Various mechanical locating devices have been used widely to assist the blind in performing tasks that would normally require vision.

This is one of the great fields for further development, although it must not be imagined that the majority of the blind will become gainfully employed as soon as the engineer, working with medical, social, and behavioral scientists, has attacked the problem. The majority of the blind are too old to be considered in the normal working force. Many of them have other disabilities and, in many cases, they are not sufficiently good travelers to be able to work steadily.

Conclusion

Much has been said about problems resulting from loss of vision and little about problems resulting from loss of hearing. The other senses have not been discussed. This is chiefly because relatively little effort has been devoted to these problems; the priority of solution has not been nearly so high as in the areas of vision and hearing.

While much has been accomplished in providing devices that have found their way into general use in alleviating some of the discomforts of sensory loss, a great deal more remains to be done. We have merely scratched the surface of many of these problems; the solutions will come only as more people become aware of the need for additional work on them.

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PSYCHOLOGICAL ASPECTS OF SENSORY DISABILITY

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The major value of an interdisciplinary publication such as this depends on the degree to which physicists, engineers, biologists, and psychologists are able to communicate to each other some understanding and appreciation of the scientific problems they face in their respective fields. I do not plan to report results of new psychological research, or to address myself to my fellow psychologists. Instead, I propose to describe briefly the progress made thus far in psychological research on physical disabilities, to tell how this progress has been achieved, and to define future objectives.

Further limitations on this presentation are also desirable. Psychologists have far-ranging interests; they do research on many seemingly unrelated topics. The work some of us perform is more closely related to that of biologists, physiologists, and engineers than to that of other psychologists. In part, some of the people and the research we might claim for psychology also are claimed by other disciplines. With respect to sensation, perception, and sensory disorders, the merging of disciplines started with G. T. Fechner, W. Wundt, and H. von Helmholtz almost 100 years ago and has continued at a rapid rate ever since. On many frontiers of sensory and perceptual research some psychologists are working with the same variables and on similar problems as their colleagues in the physical and the biological sciences.

The *Handbook of Experimental Psychology*¹ offers an excellent compendium of psychophysical work on the senses; I think it is undeniable that psychologists have been both great contributors and consumers of knowledge in this field. However, I feel reasonably certain that the results of this kind of psychological research are well known to engineers and physiologists. No doubt representatives of these latter fields know better than many psychologists the work of such eminent, living investigators as Bartley,² von Bekesy,³ Boring,⁴ Davis,⁵ Geldard,⁶ Gibson,⁷ Hebb,⁸ and Riggs,⁹ to name only a few.

For these researchers and their intellectual ancestors, the raw data of sensation and perception have been immediately meaningful; at least, the data could be ordered readily to genotypical variables.

There are other fields of psychology, however, in which sensory status and physical processes may be considered purely phenotypic. They do not have direct genotypic, psychological meaning. In somatopsychology, for example, a sensory disability as a physical fact has the same meaning for the psychologist as eye color to the geneticist or red stones to the geologist. That is to say, concrete but phenotypic data such as eye color alone will not permit precise genetic predictions, and will not permit an understanding of the hereditary transmission of physical characteristics. It is necessary first to ascend the ladder of abstractions and invent genotypic concepts to which the raw data can be ordered. So, too, there is an area of psychology in which

physical variations appear to be related to behavior, but psychological predictions can be made from these concrete physical data only with a great margin of error, and with possibly little understanding of the "exceptions to the rule." This is the problem area principally described in this paper.

The basic argument is that physique, including sensory disorders, is phenotypic for psychological behavior. By this I mean that once one has stated that a deaf person does not perceive auditory stimuli or engage in listening behavior and a blind person does not perceive visual stimuli or engage in looking behavior, that is *all* that can be said with precision. Individuals with impaired hearing vary tremendously, and so do individuals with impaired vision; but their behavior varies in ways that are only indirectly or peripherally related to their sensory losses. This is not to say that there are no behavioral uniformities among the deaf and the blind. There are, but there are also many exceptions that we cannot explain. Some of my clinical colleagues are quite willing to tolerate these exceptions. They talk in terms of error variance that is to be expected, and they feel that an aspiration for 100 per cent predictive efficiency in psychology is a delusion—a goal that will never be achieved.

Some of us do not agree. We feel that unless we can show a *must* relationship, we do not really understand—that is, it is necessary to show not only that some phenomenon occurs but that, in the context of the person's characteristics and his behavioral field, the phenomenon *must* occur. Explanatory principles of this kind must explain both the behavior that occurs as a rule and the behavior that occurs as an exception.

It seems unlikely that these aspirations will ever be achieved so long as we accept physical variations as immediately meaningful psychologically. As every other mature science has learned, it is necessary to transform raw data to concepts and parameters relevant to the predictions that are to be made. Physique is not directly a psychological variable. It is a physical variable, and the problem is how to make psychological sense out of non-psychological data. One answer, clearly, is to invent concepts that will permit the transformation of physical variables to psychological variables.

In the past this transformation of the physical data to psychological data has not often been undertaken. Instead, we have tended to accept physical characteristics such as deafness and blindness as psychologically meaningful. However, even making allowances for some methodological errors that this orientation almost inevitably introduces into research, the results of our study have not been very enlightening.

The following, I think, is a fair summary of what the bulk of past research has shown:

(1) People who have physical disabilities tend to have more frequent and more serious social and emotional problems than people who do not have physical disabilities. There are many exceptions, however. Perhaps 30 per cent of the individuals who are disabled have been found to be as well or better adjusted to life—by whatever psychological criteria we choose to use—than the average nondisabled person.

(2) The more severely disabled person tends to have more frequent and

more serious adjustment problems than the less severely disabled person. Again, however, there are many exceptions. A large number of marginally and moderately disabled persons appear to be less well adjusted than many seriously disabled individuals.

(3) The longer a disability exists, the more serious is the psychological disturbance found in the disabled individual. This is not uniform, of course. Recently disabled persons may be more seriously disturbed than others who have been disabled a long time.

(4) Different kinds of disabilities appear to coerce different kinds of behavior. While there is a great deal of variability in persons having the same kind and degree of disability and a great deal of overlap in the behavior found among individuals having different disabilities, the uniformities seem striking enough to generate concepts such as the deaf personality, the blind personality, or the polio personality.

(5) The problems of adjustment faced by the disabled are rooted in their physical limitations; therefore, disabled persons face personal problems unknown or almost unknown to nondisabled people. The same degree of physical impairment, however, does not necessarily give rise to the same degree of impaired function. Again, precise specification is difficult.

Until the late 1940's this was about as far as psychology had advanced in its understanding of the social psychological effects of disability.

Much of the literature amounted to no more than a claim that behavior depended upon the individual case. Each case was different and required unique treatment. If there was "lawfulness," it was only of an actuarial kind. For example, employed disabled people tend to live more satisfying lives than those who are unemployed. Of course, a person could be both employed and highly maladjusted, but that would be an exception—a fairly common exception, but still not the rule. Understanding was meager, prediction hazardous, and treatment often ineffective because, it was said, consideration had to be given to the complex interaction of the multiple variables that may influence behavior in a particular case.

In effect, we in somatopsychology had a clinical discipline that was often of great value to individuals, but we did not have a science. We were like the social workers during the depression of the 1930's, who could give great help to a few selected individuals who were out of work, without understanding or attempting to solve the larger problems that caused the unemployment of millions. In psychological work with the disabled, we do not have, and perhaps never will have, the number of skilled clinicians necessary to diagnose and treat each case individually. Moreover, it is wasteful to consider each case almost as if it were unique and as if behavior were not lawful. It is good and necessary to solve individual problems, but it is necessary also to devote equal effort to the search for explanatory principles that alone can lead to understanding, prediction, and control. The goal, as in all science, is to discover general laws that can be applied to the individual case. Certainly, adjustment to disability depends on the individual case, but on *what* in the individual or his culture does it depend? What is it that must be changed or

manipulated? Until recently, we had few leads that might answer this question.

Obviously, physique and behavior are associated in many ways. It is not easy to disentangle the effects of physiological, genetic, psychosomatic, sociological, constitutional, and social psychological variables, for these variables probably never operate in isolation. Nevertheless, many of these relationships have been studied intensively and with considerable success, although the purely psychological and social significance of physique—the somatopsychological relation—has been more a subject of casual observation, folklore, and speculation than of research.

Fortunately, a few giants appeared on the scene. No doubt I am biased here, since the researchers and theoreticians to whom I refer are my teachers and colleagues, but perhaps it is significant that, even after close association with them, I still see them as giants. They are Roger G. Barker and Beatrice A. Wright of the University of Kansas, Lawrence, Kans., and Tamara Dembo of Clark University, Worcester, Mass. All of them, incidentally, were students of the great Kurt Lewin¹⁰ and they rely on his basic theoretical orientation.

Partly because there was ample clinical evidence that some of the most important sources of personal maladjustment in disability were functions of physique in its role as a stimulus to the self and to others, Barker *et al.*¹¹ made a comprehensive survey of the relevant literature and attempted to bring order into this field by generating concepts to describe and explain what was known. They found that the first three of the five summary points stated earlier were congruent with the evidence. Studies of disabled persons did show consistently both group uniformities and extreme individual variations in behavior, although the relevant variables that coerced the behavior were rarely clear. The fourth and fifth summary points, however, were not tenable. Instead, these two points may be restated as follows:

(1) Within a wide range of different disabilities, the kinds of behavior and the kinds of disturbances found do not differ. The deaf, the blind, and the crippled do not behave in psychologically different ways. The content of their adjustment problems is different, but when the raw data are transformed to psychological parameters, the behavior is seen to be similar.

(2) The personal adjustment problems of disabled persons are not unknown to the nondisabled; they are of the same kind. Certain kinds of problems such as fearful, shy, and self-conscious behavior may occur more frequently among the disabled and have more complex determiners. There is no question of uniqueness, however. The same psychological principles that hold for the physically normal person are generalizable to the disabled.

It was an easy conclusion, therefore, that physical disability predisposes toward psychological maladjustment but that it does not require it. Physical disability, in more precise language, is neither a necessary nor a sufficient condition for psychological maladjustment. Psychological maladjustment depends on psychological variables. What, then, are the psychological variables on which adjustment depends?

This problem became important to our colleagues in the physical sciences when they found, to their surprise, that the proverb concerning the better mousetrap was not true. You can build a better artificial limb, but it will not necessarily be used by those who stand to benefit from it. You can build a better hearing aid for those with impaired hearing and better guidance devices for the blind, and your gadgets, perhaps more frequently than not, may end up in a closet or a bureau drawer.

As we have seen, the evidence indicates that the locus of physical disability is not a critical variable. People with different kinds of disabilities do not seem to behave in psychologically different ways. Moreover, their behavioral maladjustments appear to differ from physically normal individuals only in quantity and intensity and not in kind. More generally, physique per se does not appear to be central to any psychological variable, and a condition of disability directly coerces only physical behavior. It seems evident, therefore that, if physically handicapped persons have psychological difficulties, these difficulties do not stem directly from physique, but have been mediated by the social psychological situation created by variations in physique.

A simple example may make this argument clearer. There are some individuals in our culture who have excellent hearing for tones of 15,000 to 20,000 cycles per second. Many people, however, cannot hear tones above 10,000 cycles per second. This inability to hear tones of higher frequency is a physical disability. We can measure the degree of loss precisely. However, since hearing for high frequency tones is not important in our culture, this disability does not appear to have any psychological effects. It is a disability without psychological concomitants. A similar statement can be made about some visual disabilities.

Our approach then, in somatopsychology, must change from a direct concern with physical variables. It is neither important nor relevant for psychologists, as distinct from public health and sociologists and social welfare people, to ask questions concerning such factors as the group characteristics of those with sensory disabilities. Rather, the basic questions are the following. How may physical variations be mediated so as to have psychological effects? What are the laws that govern this relationship or, in terms of what concepts can the observed phenomena be understood?

Essentially, I contend that there are three levels of investigation in the psychological study of disability.

The first level starts with the assumption that physical deviations must have direct psychological effects. Most of the research in the past has been on this level. We ask: what is the intelligence or the ego strength of disabled people? What kind of defenses do disabled people use? How self-reliant or dependent are the disabled? This kind of research has not been productive. The answer has always been that there are great individual differences and only weak group trends. To be sure, I think this kind of research serves a public health function in informing us indirectly of some important social problems, but it will not solve these problems because it tends to be simply fact finding without the conceptualization that will give meaning to the facts.

A second level of research we may call somatopsychological research. Here

we are concerned not only with the isolation of a particular class of behaving organism—the physically disabled—but also with the more general problems of how and why physique may affect behavior. This level of research differs from the first level largely in its “directedness” and abstractness. It is based on a theory that specifies both the kind and the direction of phenomena that will be observed, and it concentrates on transforming the nonpsychological data of disability to psychologically meaningful concepts. As in animal and child psychology, which also begin with the observation of a particular class of organism, the development of practical psychological techniques is often a by-product of the search for more fundamental knowledge.

Somatopsychological research emphasizes the effects on behavior of the situational forces that are induced by variations in physique. The basic approach is that behavior, in large degree, is relatively independent of physical characteristics. Instead, other things being equal, behavior is a function of the situation in which a person must act. Anyone placed in the same social psychological situations common for the disabled would behave in the same ways.

It is hypothesized that the structure of the situations in which disabled people behave is different from the situations of others in the following respects. The situations, more frequently, are psychologically new; that is, ambiguous both for the disabled person and for those with whom he interacts. It is often not possible to be certain in advance just what results will occur until after a situation has been entered. It is a situation without certainty and without security. It is a situation in which humiliating mistakes are inevitable. In addition, the disabled person more frequently enters situations in which he is simultaneously subjected to psychological forces that are antagonistic. He is a marginal person who, on the one hand, is urged to be as normal as possible when he lacks the tools to behave normally and who, on the other hand, can achieve security only by accepting what seems to be a less desirable position in society and less desirable goals. He lives on the threshold between two psychological worlds; the world of the physically normal, which contains desirable physical and social goals that may be extremely difficult or impossible for him to attain, and the underprivileged, ambiguous world of the disabled.¹²

The psychological consequences of persistently being subjected to new psychological situations and to overlapping antagonistic psychological situations have been spelled out in the literature.¹³ The derivations from the theory seem to be in good agreement with the behavior of disabled persons who are psychologically disturbed.

This approach achieves the following advantages simultaneously:

- (1) It shows us one way in which disability may mediate psychological disturbance.
- (2) It explains the behavior of the disabled who are not psychologically maladjusted. The latter are not persistently placed in new and antagonistically overlapping situations.
- (3) It tells us what to do to reduce psychological disturbance; that is, to reduce the frequency with which new and overlapping situations are entered

and thereby avoid the marginality, the conflict, and the insecurity that accompany such situations.

(4) It is generalizable to any other class of organisms placed in new and overlapping situations. Others will behave the same way as many of the disabled do. The behavior of minority groups, for example, is dynamically similar to the behavior of the deaf and the blind, and for the same reasons.

The highest level of research and conceptualization may ignore nonpsychological data entirely and concentrate completely on psychological processes. Here we are concerned with such psychological variables as the nature of misfortune, the nature of suffering or, more generally, *losses* of any kind. Tamara Dembo and her colleagues¹⁴ have brilliantly spelled out this approach, considering misfortune as a psychological event that may be conceptualized as a value loss. Anyone who has experienced a misfortune or a psychological loss is subjected to similar psychological forces. The disabled are simply one group whose members have experienced misfortune. There are many others, including those as apparently diverse as spinsters, parents of mentally retarded children, and the unemployed. All of us, in fact, in one way or another probably have experienced value losses, and have thus behaved in similar ways.

Unfortunately, in psychology we know little about the assimilation and resolution of losses. We have been concerned mostly with the consumption of gains and the achievement of goals. Investigation of losses, however, is also possible, and Dembo *et al.*¹⁴ have made a brilliant start. They hypothesized that the physically handicapped are not perceived as neutral stimuli. Frequently the handicapped may be perceived, both by the disabled themselves and by others, as unfortunate people who have lost something of great value. Like other kinds of perception, this is a judgment that may or may not be congruent with the objective situation. If the value that has been lost has a central place in the value system of the perceiver, however, the following sequence will occur: the perceiver will insist (1) that the person who does not have any given value is unfortunate; (2) that he is suffering; (3) that he "ought" to suffer; in other words that it is appropriate that he mourn his important loss; and (4) that he is less worthy than others and less valuable as a person.

Dembo *et al.* then state the conditions under which this sequence and its consequences will vary. As in other good theories, therapeutic actions or the requirements for change are directly derivable. A major conclusion is that it is not the objective physical loss from which a disabled person suffers, but the value system of the judge who assigns or withholds devaluation of the "total person." Some testable hypotheses relating value change to adjustment are evident immediately.

It is clear that the theory of misfortune also permits the transformation of physical data to psychological data, and it offers general principles that may be applied to the individual case.

In summary, therefore, psychologists are beginning to free themselves from a common-sense dependence upon physical variables as basic determiners of psychological actions. They have developed at least two rigorous, scientific-

cally sophisticated, and testable theories that relate some aspects of physique and disability to some aspects of behavior. In the future, as these theories are elaborated and subjected to experimental verification, and as additional theories of high conceptual clarity are formulated, it will be seen that the psychological phenomena of sensory disability are as lawful and as subject to understanding, prediction, and control as are physical phenomena.¹⁵

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RESEARCH IN SENSORY DISORDERS

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INTRODUCTION

To understand sensory disorders, investigations must be conducted in both the basic sciences and the clinical disciplines. In recent years, with the development of new electronic, physical, chemical, and psychological techniques for the studies of sensory stimulation, perception, and sensory disorders, the variety of attacks has increased. It is not surprising, therefore, to find a physicist in the Netherlands working on the psychophysiology of vision, a psychologist in Bethesda, Md. observing sensory stimulation and analyzing subjective reports of a patient undergoing temporal lobectomy, or a physiologist in Stockholm, Sweden working on the biochemistry of retinal pigments. In many current investigations, teams of scientists are working together and pooling their talents in order to solve the more complex problems.

The purpose of this paper is to present examples of recent research that illustrate the variety of the contributions of the physical, biological, and psychological sciences to the understanding of sensory dysfunction. The coverage is not comprehensive. The specific examples chosen may be multiplied several times by referring to the reports of other investigators working on the same or related problems.

RESEARCH IN VISION

Fine Structure of the Ocular Media

The development of the electron microscope has opened an entire new vista of research on the ultrafine structure of the nervous system and the sense organs. For example, Marie A. Jakus, at the Retina Foundation in Boston, Mass., is conducting a long series of studies on the cornea of the eye.¹ She finds that Descemet's membrane, previously thought to be without structure, is characterized by a very fine structure of great regularity. She speculates that this fine structure, when held under tension, may serve as a collimating device to incident light. Supplementary information has been obtained from the developing chick embryo. The same fine structure has been found during the differentiation of Descemet's membrane. Other investigators, using the technique of X-ray diffraction, have come to the conclusion that this membrane belongs in the collagen class of proteins.

In a study of a specific ocular disorder, keratoconus, Chi *et al.*,² using the technique of photomicrography, have investigated the various layers of the cornea. They conclude from their studies that keratoconus is a degenerative lesion involving primarily the anterior layers of the cornea. They report

that fragmentation of the corneal epithelium and fibrillation of Bowman's membrane occur. The destroyed tissue is replaced by newly formed connective tissue. In advanced cases, actual rupture of the cornea occurs.

The Visual Receptors

The sensation and perception of light is an extremely complex matter, especially in the human eye, with its multitude of receptors, ganglion cells and neural junctions, and complex neural tracts and way stations between the sense cell and the visual cortex. The basic approach to the study of this complex has been to go to the simpler organisms. For example, Hartline, now at The Rockefeller Institute for Medical Research, New York, N. Y., has been studying the details of the response of the single sensory receptor of the eye of the limulus, the horseshoe crab.³ By means of electronic equipment he has been able to measure thresholds of response, inhibition, adaptation, and other aspects of the visual function. The interesting discovery of the inhibitory interaction of the receptor units in the eye of the limulus has been made. Hartline has found that the stimulation of an adjacent ommatidium has reduced the frequency of discharge of impulses from its neighbor. "When only two ommatidia are illuminated, the magnitude of the inhibition of each one depends only on the degree of activity of the other; the activity of each, in turn, is the resultant of the excitation from its respective light stimulus and the inhibition exerted on it by the other."

Working with the eyes of frogs and cattle, as well as the photoreceptors of insects and plants, Wolken⁴ has made a comparative study of photoreceptors. Again, using the electron microscope, he has measured the dimensions and observed the ultrafine structure as well as the concentration of pigment in them. He finds a general lamellar fine structure common to all of the photoreceptors. His measurements of spectral sensitivity show an absorption in the neighborhood of 500 m μ , that of the carotenoids. The activation energy of bleaching, as calculated by him, was the same for algal chloroplastin and for the rhodopsin found in the eyes of frogs and cattle.

Still another basic approach to the study of sensory disorders is a biochemical one. For many years, by means of microchemical techniques, Wald⁵ and his group at Harvard University, Boston, Mass., have been investigating the chemical processes that take place in the eye during light and dark adaptation. He has been able to identify and reproduce the various steps in the chemical transformations that occur in vertebrate eyes.

As is well known, the retinas of most vertebrate eyes have two kinds of light receptors: rods for vision in low illumination and cones for vision in high illumination and for color vision. In these end organs there is a photosensitive pigment that is bleached on exposure to light. As a result of this process nervous excitations are initiated and transmitted over the optical pathways to the brain, where visual sensations are aroused.

Wald has identified four pigments: rhodopsin and porphyropsin in rods, and iodopsin and cyanopsin in cones. Each of these pigments is composed of a carotenoid color group united with a specific protein or opsin. Two types of opsin are known: scotopsin in rods, and photopsin in cones.

An enzyme, alcohol dehydrogenase, and a coenzyme, cozymase, and retinene participate in the reactions.

These brief statements summarize many years of effort by Wald and his group. They have contributed a great deal to the understanding of the biochemical factors involved in the perception of light and color.

In spite of his love of basic research, Wald has always maintained contact with clinical problems in vision. For example, he and Zeavin⁶ have made a careful study of rod and cone vision in retinitis pigmentosa. The cause of this blinding disorder is unknown, and there is no treatment. It runs in families, occurring rather frequently, and has a slow, progressive course. Peripheral vision is lost gradually, ending in what is known as tubular or gunbarrel vision.

Since rod vision deteriorates much more rapidly than cone vision in retinitis pigmentosa, it has been suggested that the disease may be associated with some local failure in the supply of or ability to use vitamin A. Wald and Zeavin suggest that either the neo-*b* isomer of vitamin A, which is prerequisite for both rod and cone vision, is not formed, or is used up at a greater rate of speed by cone opsin. Thus, a failure to form this isomer, or an inadequate supply of it, would lead to failure in vision.

Diagnostic Procedures

Several new diagnostic procedures deserve rather brief mention. For example, the electroretinogram permits the determination of an intact retina in spite of opacities of the ocular media that prevent its visualization. Among many studies of this technique, only one will be mentioned here. Auerbach and Burian,⁷ at Iowa City, Iowa, have investigated photopic-scotopic relationships. They found two superimposed curves of slightly different latent periods that are related to these two types of responses. Their studies at various levels of light adaptation show a characteristic graph, the expression of an equilibrium between bleaching and resynthesis of the photopigments.

Lowenstein,⁸ at the Institute of Ophthalmology, Columbia University, New York, N. Y., has developed a pupillograph for recording the movements and reflexes of the pupils of the eyes. He is able to test the reactions to light, to darkness, to near vision, and to psychosensory stimuli. In addition, he is able to make studies of the effects of drugs upon the pupillary reflexes. By analyzing his data, it is possible to find the factors by which, on the various levels of central control, the movements are integrated under normal and abnormal conditions. The equipment has been developed so that a direct-writing electronic instrument automatically records the pupillary diameter under the various conditions of light, drugs, fatigue, and emotion.

The use of the electromyograph, which has been valuable in studies of disorders of muscle, has been extended to the extraocular muscles of the eye. Breinin,⁹ of New York, N. Y., one of the investigators using this technique, states that the theory that awareness of the position of the eyes due to proprioceptive impulses from these muscles which was strongly advocated by Sherrington has been denied. It has been considered that the cues received from vision and from the innervation to convergence are sufficient to explain the awareness of the position of the eyes.

Breinin states further that, if the extraocular muscles do not have proprioceptors, they represent an unexpected exception to the rest of the skeletal muscles. He has demonstrated that a mechanism does exist for signaling changes in the tension of the extraocular muscles. This provides a new tool for studies of oculomotor anomalies of the eyes. Other methods are largely subjective, depending upon the report of the patient being examined.

Glaucoma, which is characterized by increased intraocular pressure, occurs in 2 to 3 per cent of the population over the age of forty. If detected early, the pressure can be controlled and blindness can be prevented. Because of its insidious onset, however, this disease is often overlooked, although its presence can be detected simply by using a tonometer, which measures intraocular pressure directly. A very simple device has been developed for screening purposes, and can be used easily by general practitioners in routine physical examinations.

Becker¹⁰ reports on a new laboratory procedure called tonography, which makes it possible to estimate the rate of secretion of aqueous humor and the rate of its outflow from the eye. By means of continuous electronic recording of the intraocular pressure during compression of the eyeball for four minutes, the degree of impairment of outflow as well as the increased pressure of glaucomatous eyes can be estimated. In addition, following the consumption of a liter of water, a decrease occurs in the outflow facility of glaucomatous eyes as compared with the normal.

Becker concludes that prompt effective treatment with miotics, carbonic anhydrase inhibitors (Diamox), and surgery can prevent the progression of the disease which so often results in blindness. Some of the other workers on this problem are W. Morton Grant, Elmer J. Ballantine, and Frank J. Macri.

O'Connor,¹¹ a research associate at the National Institute of Neurological Diseases and Blindness, has devised an agar diffusion technique for aiding in the early diagnosis of the blinding disease toxoplasmosis. When the fluid from the aqueous humor of the affected eye is allowed to diffuse through a semisolid agar gel, visible lines of the precipitation reaction characteristic of toxoplasmosis occur. A clinical follow-up study made by O'Connor one year later has demonstrated the value of a specific diagnosis of ocular toxoplasmosis during the early stages of infection, which allows for effective treatment before permanent damage can occur.¹²

A Visiting Scientist at the National Institute of Neurological Diseases and Blindness, Chie Tanaka,¹³ of Tokyo, Japan, has reported a new modification of the agar diffusion technique described above which may be used in studies of immunity to adenoviruses. She has demonstrated precipitating antibodies against the virus of an inflammatory eye disorder known as epidemic keratoconjunctivitis.

Retrolental Fibroplasia

In a symposium on retrolental fibroplasia, Patz¹⁴ summarized the history of the development, study, and elimination of this blinding eye disorder in premature infants. The disease was first reported by T. L. Terry in Boston, Mass., in 1942. Since that time the incidence of retrolental fibroplasia in

the United States, England, the Continent, and Australia has increased rapidly. V. Kinsey and L. Zacharias in 1949 first called attention to the use of high concentrations of oxygen on human babies as a possible cause of the disorder.

The first controlled study of human infants exposed to high concentrations of oxygen was made by Patz *et al.* in 1952.¹⁵ Both Ashton¹⁶ and Patz^{17, 18} did the early work with animals, and published their conclusions almost simultaneously in 1953.

In 1953, a group of ophthalmologists and pediatricians, under joint research grants from the National Institute of Neurological Diseases and Blindness, the National Foundation for Eye Research, Boston, Mass., and the National Society for the Prevention of Blindness, New York, N. Y., undertook a cooperative investigation of oxygen as a possible factor in the disease. With Kinsey¹⁹ of Detroit, Mich., as chairman, a coordinating committee directed a carefully controlled clinical study in eighteen hospitals throughout the United States.

The results verified the early hypothesis of Kinsey and Patz, that the excessive administration of high concentrations of oxygen was the critical factor. As soon as the preliminary findings were released, hospitals all over the country discontinued the use of oxygen in premature nurseries except in cases of emergency, and then only in concentrations under 40 per cent for brief periods of time. Since 1942, over 2000 babies had been blinded for life. After the release of the results of the study to all hospitals, pediatricians, ophthalmologists, and general practitioners in the United States, the incidence of the disease dropped from approximately 20 per cent to less than 1 per cent.

One of the important psychological studies related to retrolental fibroplasia was directed by Ward C. Halstead. The greatly increased number of blind babies in the past 20 years had raised serious problems in training and education of these afflicted children. Halstead and his associates made systematic observations of 317 blind children (69 per cent blinded by retrolental fibroplasia) anterospectively over a period of 6 years. A number of their conclusions are worth summarizing briefly.

Norris *et al.*²⁰ concluded that retrolental fibroplasia is not a generalized neurological condition in which there is an associated brain defect. In other words, the damage is localized in the retina, as had been shown by Patz and Kinsey. Norris and his associates believe that a blind child, under optimal conditions, " . . . can develop into an independent, responsible, freely functioning child whose use of his potential compares favorably with that of most sighted children of his age." They state that the way such a child functions is not determined by the degree of blindness, his intelligence, the socio-economic, or educational background of his parents, or even by the presence of other physical handicaps. They point out also that "The earliest months of the blind child's life and the years of the preschool period are of primary importance. . . ." and actually " . . . determine the course of his later development." They state further that "The failure to provide the essentials for healthy personality development may result in grossly retarded functioning and extreme emotional problems that do not lend themselves well to treatment. . . ."

RESEARCH IN HEARING

Sound Conduction in the Ear

Wever²¹ and his associates at Princeton University, Princeton, N. J., have investigated the transmission of sounds from the air to the inner ear. They find that two mechanical factors are important. One is the lever ratio provided by the small bones of the middle ear. The other is the hydraulic ratio provided by the tympanic membrane and the footplate of the stapes. These mechanical advantages produce an increase in the pressure so that the transfer of energy from the sound waves to the fluid of the inner ear is made without loss. Wever has found also that the action of the tympanic muscles of the middle ear provides a protection of the inner ear against overstimulation by sounds by controlling the displacement of the ossicular chain from its normal operating position.²²

Auditory Tracts

The discovery of efferent auditory tracts is leading to a reconsideration of the neurophysiology of auditory perception. Rasmussen,²³ formerly at the University of Buffalo School of Medicine, Buffalo, N. Y. and now at the National Institute of Neurological Diseases and Blindness, has demonstrated descending or "feed-back" connections in the auditory system of the cat. Descending degeneration, following lesions of the inferior colliculus and/or dorsal nucleus of the lateral lemniscus, project to the site of origin of the olivocochlear bundle, whose fibers terminate in the cochlea. The experimental findings suggest that the dorsal cochlear nucleus plays an important role in control over cochlear afferent impulses received by the central cochlear nucleus.

Rasmussen has developed also a new silver stain, which has been tested on various synapses in different regions of the central nervous system.²⁴ The clarity and completeness of staining contribute to present studies of interneuronal relationships by the experimental method of Wallerian degeneration. The disappearance of synapses of damaged neurons can be noted, and the relative number of synaptic connections affecting a single nerve cell that originates from different anatomical and functional sources can be determined.

Disorders of Hearing and Auditory Perception

Both military and industrial situations have magnified the problem of nonorganic hearing loss. Tests for malingering and psychogenic deafness have been developed, but such tests usually do not measure the threshold of hearing.

Goldstein²⁵ reports that, although the electrodermal response test seemed to offer promise of providing a measure of threshold objectively, his study showed that the lack of responses to tone on the test could not always be equated with an organic hearing loss.

Goldstein and his associates,²⁶ in approximately 50 cases of infantile hemiplegia in which hemispherectomy had been performed, found that auditory thresholds and the understanding of speech were normal prior to and following

surgery. "While the cerebral abnormality which led to infantile hemiplegia did not disturb the speech and language of most of the patients, it prevented a few of them from developing useful speech."

In their study, quantitative measurements of hearing and evaluation of the speech of four patients with right infantile hemiplegia, before and after hemispherectomy, were reported. The audiometric records following hemispherectomy did not differ significantly from the preoperative records.

"The patients' speech, while somewhat lacking in proper control of loudness or tempo, gave no evidence of aphasia. Vocabulary and language were commensurate with intellectual capacity and level of education"

There was a significant impairment in the discrimination of different words. On the average, 45 per cent of the words were missed in the right ear (contralateral to pathological hemisphere), while only 20 per cent were missed in the left ear (contralateral to the intact hemisphere).

Hallowell Davis (personal communication), at the Central Institute for the Deaf, St. Louis, Mo., has reported the results of psychophysical studies of the perception of rhythmic patterns. This perception, he states, is initially more accurate for auditory than for visual or tactual stimulation. Such differences, however, disappear with learning. Davis and Shickman²⁷ reported that the perception of temporal duration seems to be based upon an additive mechanism of discrimination—a systematic time-order effect.

Rosenstein,²⁸ who worked with Davis, stated that the auditory sense seems to process rhythmic information better than does the visual sense. He reported that deaf and aphasic children who have been deprived of normal auditory experience do not perceive factual rhythmic patterns any less accurately than a group of normal children. Blind children, however, seem to do better.

In a discussion of nerve deafness in children, Goodhill,²⁹ of Los Angeles, Calif., concludes that recognition of the Rh factors and other blood incompatibilities between mother and infant has stimulated research on the auditory pathway. His results suggest that this pathway is not a simple afferent tract. He has found that lesions may occur in the central or vestibular nuclei, thalamic or subcortical regions, or in the reticular formation. This variety in the location of neural damage suggests the extreme complexity of nerve deafness resulting from perinatal factors, and poses extremely difficult problems of diagnosis.

Electrophysiology of the Auditory System

Tunturi,³⁰ at Portland, Ore., is mapping and measuring the cortical areas that show a response to sound. He has developed a complex electronic recording system with multiple electrodes and multiple oscilloscopes. A data reduction system is necessary to permit analysis of his findings. In one of his simpler devices Tunturi used 10 electrodes placed on the auditory area of the dog. These electrodes were connected to 10 oscilloscopes through appropriate amplifiers, and the electrical responses to sound were recorded by photography. In a study of masking of cortical responses, he used various levels of intensity and frequency of pure tones. In the analysis of his results

he compared this masking effect in the dog with that measured with human subjects. His latest effort involves the use of a 50-channel cathode ray oscilloscope. He is recording and analyzing the electrical activity of cortical areas from unanesthetized animals, using auditory signals of known spectra and intensity. The investigation includes the measurement of latencies, amplitudes, and refractory periods, in particular, with reference to the passage of impulses through the interconnections between the various areas.

Other Sensory Disorders

Although considerable research is being done currently on taste, touch, and smell, I have selected an investigation on pain for discussion here.

According to Haugen,³¹ new concepts in neurophysiology are being developed as a result of information gained from stimulation and recording within the nervous system. Studies of normal subjects in their waking state have been made possible by means of electrodes implanted in their brains. These studies have led to investigations of pain and the effect of anesthetics. New evidence suggests that the sensory endings for heat, cold, pain, and touch are not as specific as formerly believed.

As an example of this, Tasaki and his associates³² reported on the kind of stimuli needed to produce impulses in single, unmyelinated, afferent fibers in the cat. The results of his experiments led him to conclude that a mechanical or noxious stimulus to the skin sets up impulses in more than one type of fiber. Tasaki was unable to correlate the fiber with a particular end organ.

SUMMARY

A number of examples of both basic and clinical research have been presented to illustrate the multidisciplinary approach to an understanding of sensory disorders. These examples have included studies of ultrafine structure of the sense organs and the nervous system, biophysical and biochemical measures of sensory function or dysfunction, and psychological aspects of the human response to sensory stimuli. The successful application of teamwork in the solution of one of the most baffling blinding diseases has been described in some detail.

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METHODS AND SOURCES OF STIMULATING INTERDISCIPLINARY RESEARCH

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The Respiratory and Rehabilitation Center Program, initiated in 1950 as a grant-assistance program of the National Foundation for Infantile Paralysis, Inc., is somewhat unique and most worthwhile as a method of stimulating and facilitating interdisciplinary research and of obtaining through it improved patient care by multiprofessional team effort and better integrated teaching and training programs.

In 1950, following a study of the needs of disabled patients, the foundation initiated a program for respiratory and rehabilitation centers throughout the United States. Fifteen such centers are now in operation at teaching hospitals of medical schools. They range in size from 15 to 160 beds and have a total capacity for 372 respiratory patients and 116 other severely disabled polio patients.

The nationwide study in 1949 of the problems of polio patients revealed that catastrophically paralyzed survivors were increasing rapidly in number, and that many were chronically dependent upon respirators for the maintenance of life itself. These "hopeless" patients were scattered in hundreds of hospitals where little could be done for them and where they seemed destined to remain through a tragic terminal existence.

Factors contributing to the hospitals' problem in the care of these patients included the rising incidence of paralytic polio, especially in the severely afflicted older group, and the reduction in fatality rates resulting from advances in lifesaving medical care.

These advances included earlier diagnosis and hospitalization, better clinical understanding of disturbed respiratory and other vital physiological processes, and a strengthened therapeutic armamentarium. The foundation's programs of research, public and professional education, and medical care and epidemic assistance were partly responsible for these events. Wherever polio strikes in the nation, the foundation strives to make available respirators and other equipment; often, if necessary, it supplies doctors, nurses, or technicians. To promote earlier diagnosis and care, financial assistance in the payment of hospital and other costs is assured from the initial stage of the disease.

However, without highly specialized rehabilitation facilities and services, doctors and hospitals were able to do little more for the respiratory paralytic than sustain his life. For many of these tragically disabled patients, doubly imprisoned in respirators and hospitals, survival was hardly worth the effort. Even for thousands of other severely disabled patients, quadriplegics in particular, few rehabilitation centers in the nation could even begin to provide

the services needed. Survival merely to face a pitiful and interminable hospital existence was not enough; much more was required.

Research and teaching also were desperately needed to add to our knowledge of how to help save lives and make those lives saved more worth living. The opportunity for research and teaching on a continuing basis could best be provided by concentrating these patients in groups in centers that also could care for and study acute, critically ill patients. Staffs in the centers could thus have an uninterrupted experience with the complete spectrum of the severe forms of poliomyelitis.

In addition to the humanitarian and scientific aspects of the problem, the high cost of care dictated the need for a full-scale effort to rehabilitate these patients. The estimated cost for essentially chronic custodial hospital care for about 400 respirator patients exceeded 3 million dollars for the year 1950 alone. The number of respiratory patients was to increase fivefold by 1956. Thus, for both humane and economic reasons, there was need to establish special centers where we might learn how to aid these "hopeless" patients.

The many patients with chronic respiratory paralysis, mostly quadriplegic young adults, merited our first attention. If full-scale efforts could help these most serious casualties of polio, and if humane and monetary values could be demonstrated and evaluated, then even greater benefits might be expected from a program for the many thousands less seriously involved. This logic and this need were the genesis of the national program of respiratory and rehabilitation centers that now operate in the United States.

The initial purpose of the centers was to stimulate the development of and to demonstrate and teach techniques and procedures that would enable patients afflicted with severe respiratory difficulties and associated paralyses resulting from poliomyelitis to return as nearly and as rapidly as possible to normal life. The ultimate objective was to apply the method and techniques learned from this experience, if successful, to the far greater numbers of severely disabled nonrespiratory polio patients.

The foundation invited several medical schools and teaching hospitals to accept groups of these chronic respiratory patients. It was assumed that, in these schools and hospitals, the necessary trinity of care, research, and teaching could be most directly and rewardingly supported. In these institutions it was hoped that the representatives of basic, clinical, and social sciences could collaborate in research and in improving methods for care of acute and chronic patients. The plan was to demonstrate the value of a multidisciplinary concept of care, to enlist and train allied personnel, to encourage dedicated clinical and administrative leadership, and to educate professional groups in the value of experimentation in the problems of the chronically ill.

The first two centers were established in 1950 in Boston and Houston. Others have been added gradually according to the success of the program and new regional needs. Annual supporting grants from the National Foundation have provided funds for: (1) key staff personnel (medical directors; clinical and research assistants; supervisors in nursing, physical and occupational therapy, and medical, social, and psychological services; technical laboratory

assistants; orthotists; and others); (2) special equipment and supplies for care, research, and teaching; and (3) institutional administrative and overhead expenses. In addition, the foundation's chapters have paid for the actual cost of hospital care and for adaptive equipment. The grants-in-support to 15 centers during 1957 came to a total of \$1,737,991.60.

Adequate flexible budgets enable the teams to provide the best possible care, and special personnel and equipment are made available to do comprehensive clinical evaluation and research.

In this system, care, research, and teaching form a necessary unity, and they are carried on simultaneously and in an integrated way. This unitarian attitude governs the place of research in the total activities of the center. Research and care are difficult to separate; I think we all recognize that there is a twilight zone between what is clinical investigation as a necessary part of providing better patient care and what is research per se.

Basic to the entire respiratory-center system is the fact that it operates on institutional grants from the foundation. This form of grant helps to support men working with a general clinical investigative approach. Institutional grants, unlike project-type grants, permit a flexible disposition of the centers' resources for research, care, and teaching. They allow these men to explore various leads as the investigators come upon them in the course of their clinical work. They are not bound by the budget, time limit, or agenda of the project-type research. In the final analysis, research is born of an idea of an inquisitive man; the environment or atmosphere in which he works influences him by provoking or limiting his production of ideas. When his curiosity is limited practically to definite projects, promising collateral thoughts cannot be explored until they are well formulated into another project that can invite support in the form of still another grant.

In the institutional type of grant, investigators can be opportunistic. Under this type of grant, grantees are engaged in scientific fishing expeditions; they are searching for leads as well as following up the leads already found.

The fishing ground is, of course, the patient and his problems. When, in the course of treating patients and studying their problems, a promising research lead turns up, this can be explored promptly and, if preliminary work indicates the need, additional grants for a special research project can be obtained. As might be expected, the centers' activities furnished ample opportunities for such special projects to materialize. The extent and diversity of these projects testify to the capacity of the research-care-teaching centers as fertile seedbeds for clinical and basic investigations. The practice has been for the foundation to support these as independent project grants, and the applications for them are handled through a separate advisory committee.

Thus the research activities of the centers have two sources of support: the general institutional grant for broad-scope clinical investigation, and the project grant for special studies (FIGURES 1 and 2).

It is important to note that grants to the centers do not differentiate between costs for care, research, or teaching. All of these services are deemed essential to "best possible care." The benefits and advances in care achieved

through active investigative work and teaching efforts can be considered dividends or bonuses from the center program.

There has been a growing interest on the part of medical schools and teaching hospitals in grant-support of the type extended to respiratory and rehabilitation centers. The program is one that enables the school to increase its

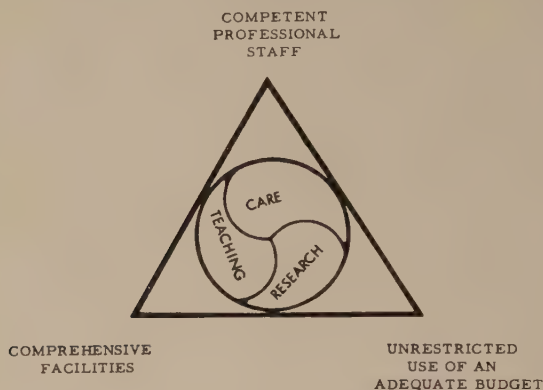


FIGURE 1. Requirements for solving the problem.

SCHEMA OF CARE-RESEARCH-INTERACTION

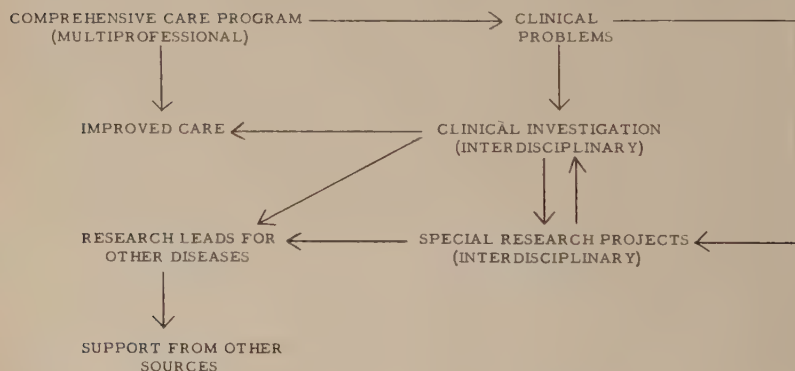


FIGURE 2. Schema for care-research-interaction.

research, care, and teaching faculty and facilities, supplies its hospital with special equipment, and supports a study group of long-term patients for whom full actual cost is paid. These severely damaged polio patients have complex physiological and anatomical disturbances. They challenge the basic sciences and the clinical arts. The intent of the center program has been to support research in any significant area that might benefit these patients. It provides for investigation on a permissive, opportunistic basis by not requiring prior formal approval of specific projects. This built-in flexibility and free-

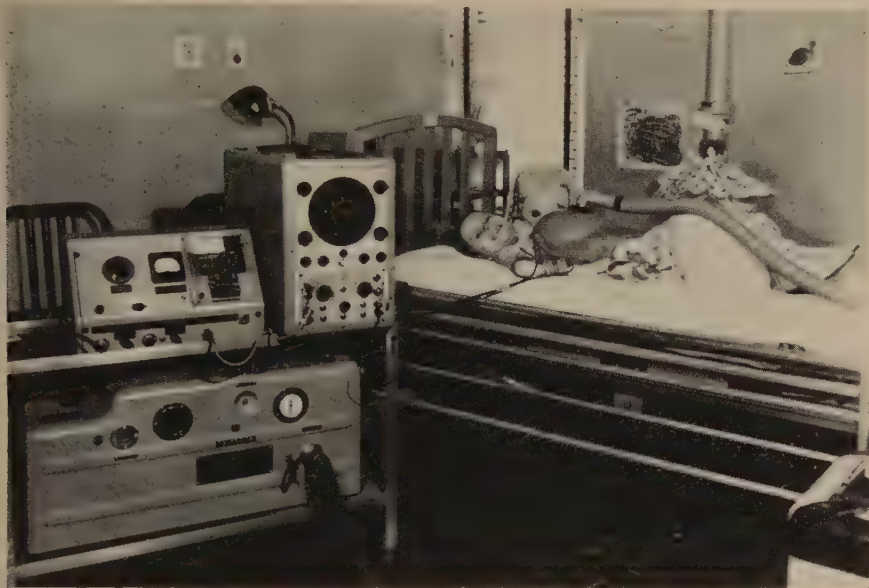


FIGURE 3. Use of the electric amplifier by a patient in a chest respirator.

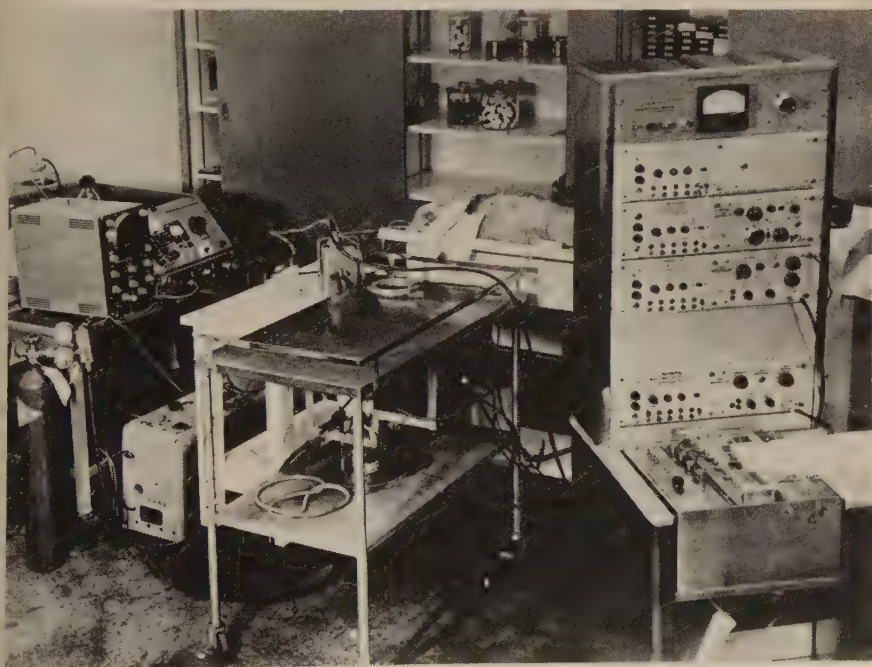


FIGURE 4. Application of the electronic amplifier in experimental animal surgery.

dom to pursue investigations of various problems as they arise has been most valuable. Grant funds for special research projects are available from many sources in the United States, but few schools and hospitals have had research funds for scientific "fishing expeditions." In this program, when a preliminary or exploratory investigation has revealed that a problem requires a more intensive or full-scale attack, either the budget can be supplemented to meet the needs or a special-project research grant can be made.

Equipment Development and Technicology

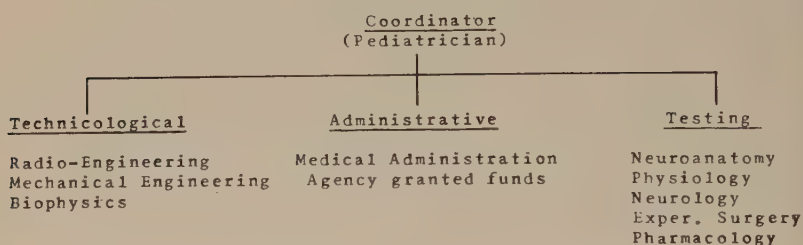


FIGURE 5. Multidisciplinary approach to basic need.

Supervision by Coordinating Staff

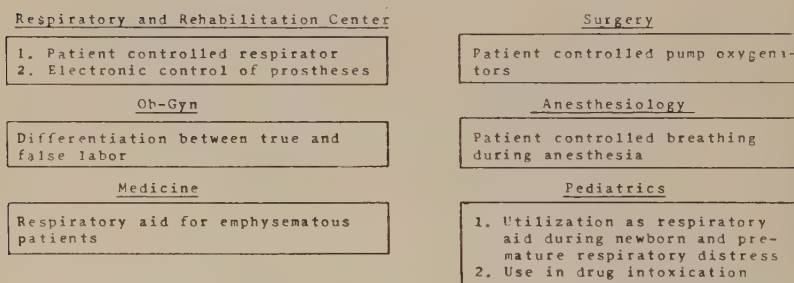


FIGURE 6. Possible application for patient care.

Let us now examine briefly some examples of the accomplishments in interdisciplinary research.

At our Respiratory and Rehabilitation Center at the Vanderbilt University Hospital in Nashville, Tenn., the basic need was felt for a tunable electronic device that, through amplification and filtration, could utilize a selected range of muscle action potentials for the activation of respirators, valves, switches, pumps, and stimulators. The center had the assistance of radio engineers in the design of an electronic device that would pick up, filter, and amplify tiny muscle-action potentials from paretic respiratory muscles. The resulting instrument can transmit these electric impulses to trigger the action of respiratory equipment (FIGURES 3 and 4). Thus, the patient's intact neuro-regulatory mechanism in the brain stem again can serve as the monitor and

control for respiration, replacing the clinician's arbitrary judgment in adjusting the respirator. In essence, the patient is again in control of the rate and depth of his breathing. This instrument is a valuable tool for research and already is being applied in other areas of medicine.

FIGURES 5, 6, and 7 illustrate the organization for multidisciplinary approach to basic need, application of the development to patient care, and interdisciplinary approach to the utilization of the development for further research.

Staff Attending Weekly Conference

Coordinator	Fellows (1)
Neurophysiologist	Student research assistants (2)
Radio-engineer	Surgeon, chest
Surgeon, experimental	

Staff Supervised Projects in Progress or Contemplated

<u>Neuroanatomy</u> 1. Neurophysiology 2. Origin of resp impulse	<u>Medicine</u> Gastrointestinal smooth muscle study	<u>Pharmacy</u> Respiratory center responses
<u>Anesthesiology</u> Reduced anesthetic deaths by patient controlled blood pH	<u>Animal Exper. Division</u> 1. Respiration control by nonrespiratory muscles 2. O ₂ saturation during sleep 3. Anesthetic effects on respiratory center	<u>Obstetrics</u> Uterine contractions <u>Medical Electronics</u> Transistorization of electrical control

FIGURE 7. Multidisciplinary approach to research utilization.

In another field of great need, that of improving the clinical management of poliomyelitis patients with scoliosis and/or flail necks, the team at the Respiratory and Rehabilitation Center at the Rancho Los Amigos Hospital in Downey, Calif., developed an interesting device called the halo; illustrated in FIGURE 8. This patient had a severe flail neck and heretofore uncontrollable scoliosis, and required a respirator for breathing. In this figure, the artificial respiration is accomplished by positive-pressure respiration at the trachea tube. The circular metal halo is attached to the skull by studs or set screws, which permits stabilization through supporting struts that derive their base of support from the pelvic band or from other devices. This device permits accurate positioning of the spine before surgery and simplifies the work of fusing the spine, as well as after-care of the patient.

FIGURE 9 illustrates degrees of correction of scoliosis occurring in respirator patients.

A further example of the remarkable results made possible through this program is the development of an artificial muscle designed to assist severely disabled poliomyelitis patients, a device representing a very important breakthrough in the field of powering orthotic devices that may benefit many more thousands of victims of paralysis from other causes. This is the first time this device has been presented to a professional body on behalf of the inventor and associated scientists and upon their request. The inventor of the

device is an experimental physicist, Joseph Laws McKibben, who has spent the last fifteen years working with the Atomic Energy Commission at Los Alamos, N. Mex., where he detonated the first A bomb. McKibben has continued to be occupied with problems of atomic energy and heads a group of physicists working with the van de Graaff. He "joined" the foundation-supported team of orthopedic and orthetic researchers at the Respiratory and



FIGURE 8

Rehabilitation Center at Los Angeles County's Rancho Los Amigos Hospital in 1955 when his daughter Karan, now 14, was admitted for rehabilitation. Karan had survived her attack of acute poliomyelitis in 1953, but was left with severely disabling residuals, including respiratory weakness, flail neck and arms, and other involvements.

During this course of treatment at the Rancho Los Amigos Center, Vernon Nickel, Chief Orthopedist, solicited McKibben's assistance in the search to find a better method to power assistive devices. The problem was defined and the seed planted. McKibben was motivated not only by his daughter's plight, but also the similar plight of many other patients at the center. With Nickel's help, he studied muscle action and physiology. In 1956 his mathematical deductions from the length-tension curve of muscle led him to a physi-

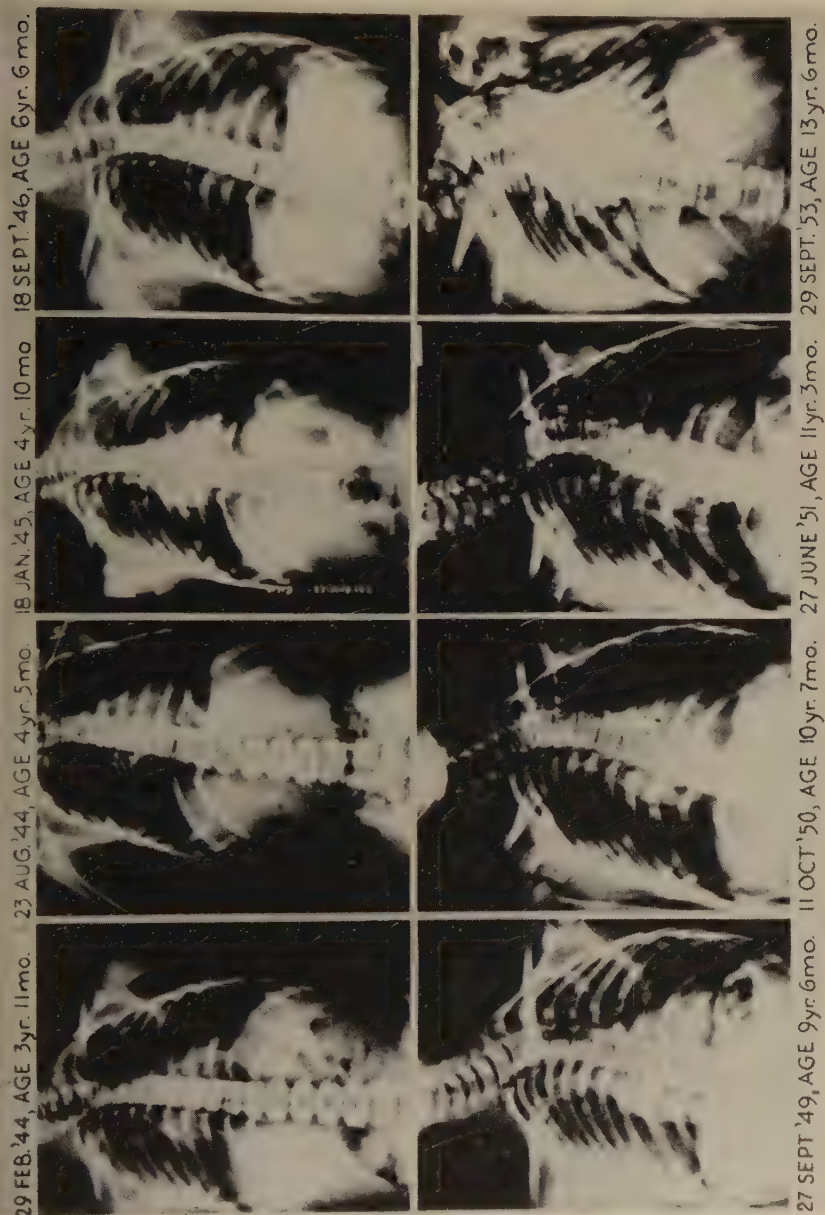


FIGURE 9. Degrees of correction of scoliosis occurring in respirator patients.

cal design for construction of an artificial muscle that would contract when "stimulated." Employing the geometric pattern of a double helix, McKibben hand-wove nylon fibers into tube form and returned to the center. There Nickel provided a rubber insert (a Penrose drain), inflated the tube with air, and observed the muscle-simulating contraction of this tube. Recently Nickel brought us this first application of this pneumatically activated artificial muscle hooked to a simple flexor-hinge splint to provide safe, effective prehension movement to flail hands. Nickel, with associate Jacquelin Perry and orthotist Roy Snelson, had developed a simple valve to provide patient control of inflation and deflation of the "muscle" with CO₂ gas from a "tire-inflater" cylinder, all of which are shown in FIGURE 10.

Electric, hydraulic, and gas-powered devices and prostheses have been used before, but none is so simple, safe, efficient, effective, and practical as this. Further developmental research and engineering and clinical trial will be necessary before this device can be made available. Even when it finally becomes so, it will necessarily be custom-built and fitted to the individual patient. With appropriate functional splinting, it seems entirely feasible to provide some essential wrist, elbow, and shoulder function to weakened or even flail arms and, perhaps, also some power-assist for paralyzed legs. Furthermore, with modification of the gas system, direct cortical control of artificial muscles seems possible through electronic amplifying devices, such as the unit developed at the Vanderbilt Center for use with respirators.

As is the case with most good things, the basic principle is simple. To speed the further development and practical application of this discovery for the use of polio patients, the foundation, through its programs in support of research and clinical investigation, will provide whatever additional support is needed. The Los Angeles Center's team will have assistance from experts in various other disciplines, and collaboration from our other centers and from the Georgia Warm Springs Foundation.

These facts are presented as an example of some of the methods and sources of stimulating interdisciplinary research used by a voluntary health organization. Modern techniques and equipment for the management of respiratory paralysis from polio (to which the centers have contributed greatly) enable doctors to save more lives and to return patients to their homes for continuing care.

Such severely disabled patients are no longer without hope and, with the future promised by this kind of advance in assistive devices, the catastrophic degree of helplessness now experienced by thousands of patients some day can be reduced. It has been estimated that there are about 50,000 poliomyelitis patients with severely paralyzed upper extremities, half of them affected bilaterally.¹ Undoubtedly there are several times this number of persons with paralyzed arms and hands from other causes, so that the problem is not a small one. Loss of hand and arm function is exceeded in seriousness of disability only by respiratory paralysis. Unfortunately, the two are commonly associated.

It is obvious, then, that any promise of a greater measure of physical independence in self care and vocational usefulness will be welcomed gratefully

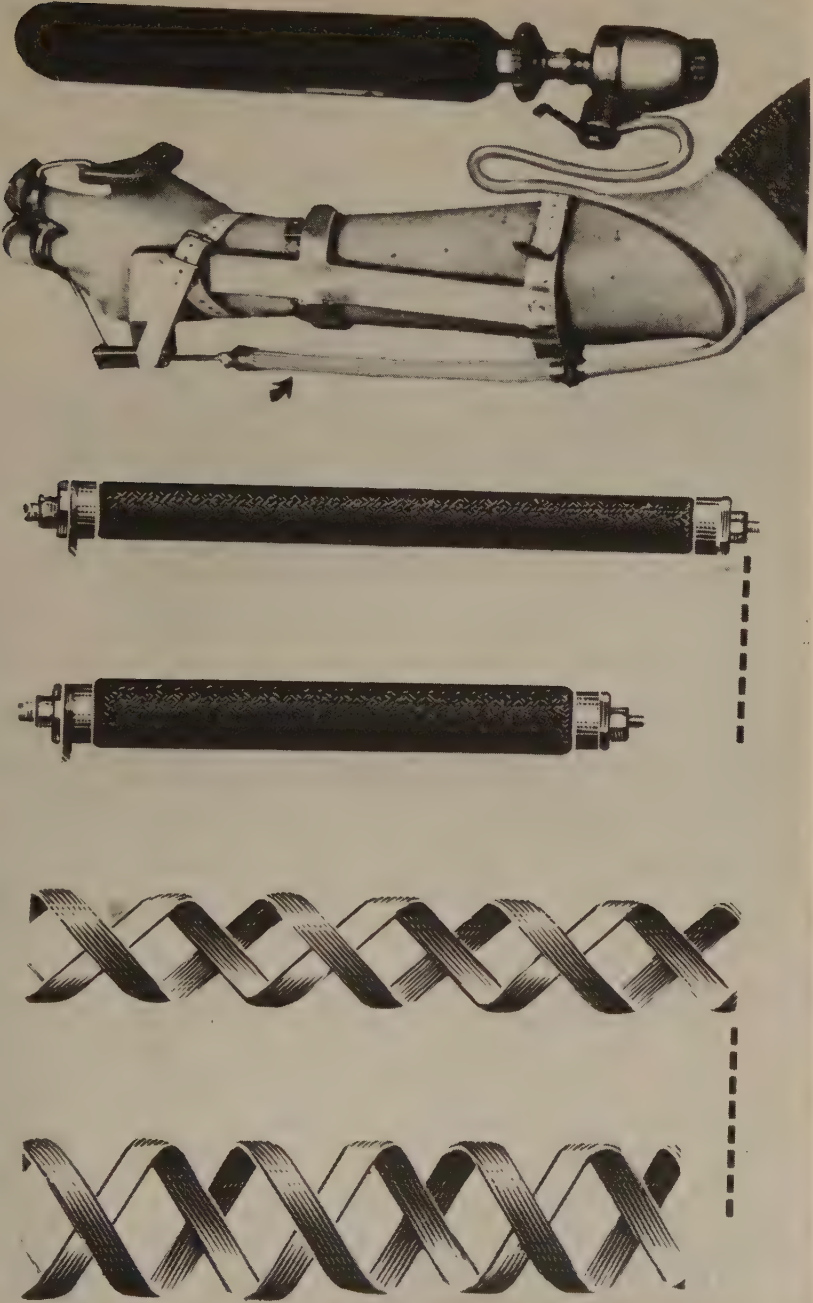


FIGURE 10

by many. What significance this discovery may hold for the development of better functioning prostheses for the amputee remains to be explored.

These illustrations of interdisciplinary research serve to demonstrate the advanced levels of understanding and acceptance that the teams have developed. The various disciplines, in their day-to-day group efforts and relationships in the care, research, or teaching of patients, develop awareness of and respect for what each has to offer, as well as understanding of their mutual interdependence. Cooperative relationships develop easily in a permissive environment under good leadership where personal dignity and professional ability are respected. Balanced staff-patient relationships and integration of services have led to unusual accomplishments by the patients. Thus the centers have been able to make an exemplary demonstration of the comprehensive organization for care, research, and teaching value that yields most successful rehabilitation results.

It is of interest to note that all of the original medical directors and most of the key personnel on their teams have remained a part of the program and have become more enthusiastic each year. This is a remarkable record, for programs of care for the chronically ill have been notably difficult to staff with well-qualified persons.

One cannot overstate the value of giving these centers both the responsibility and the freedom to investigate any problem arising in the course of their care of patients. The administration and financial support of the centers have provided for flexibility of programming to meet special problems when and as they arise, and to do exploratory study of basic issues and more extensive pursuit of them if they prove attractive. The merit of this approach is witnessed by the competence and dedication of the medical directors and their teams. The most important witnesses, however, are the patients themselves, thousands of whom have participated as members of the team, as test subjects, and as inspirational motivators to staff members of the centers and to other patients. The patients have presented each other with continuing challenges to learn more and do more. They have been grateful for each new accomplishment—big or little—that they could be helped to achieve. Considered in the aggregate, this whole program is a comprehensive research project that combines the skills of many disciplines and the facilities of fifteen medical schools in an effort to bring hope and aid to the “hopeless” chronically ill.

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Discussion

NATHANIEL J. RASKIN (*Children's Memorial Hospital, and Northwestern University Medical School, Chicago, Ill.*): I interpret Meyerson's central thesis as meaning that in order to work intelligently with disabled persons we must

understand the meaning of the disability to the individual; it is not enough to have an objective description of the disabling condition.

Support for this principle is to be found in research and clinical evidence deriving from studies of blind individuals, which indicates that the extent of visual disability per se is not significantly related to the adequacy of personal and social adjustment. I refer here particularly to investigations of blind preschool age children (Norris *et al*, 1957) and blind clients of state vocational rehabilitation agencies (Bauman, 1954).

I find support for Meyerson's thesis also in my experience as a psychological consultant on the development of technical aids for blind persons. It is difficult to think of a single device for which it was not essential empirically to discover the reaction of the potential user. This has been found to be true in the area of optical aids for those with minimal vision, in designing playing cards for this same population, in perfecting longer-playing talking books, and in marketing an audio receiver for television channels. In none of these instances could the research and development activity come to an end point in the laboratory. In addition to the factor of efficient use, it was necessary to learn what the aid meant to the individual and its impact on his relationships with others.

As regards Meyerson's "overlapping situations" concept: while this is an explanatory principle of definite value, I believe that it must be supplemented by concepts that differentiate the individual as he moves from situation to situation.

The social devaluation of disabled individuals described by Meyerson provides the basis for an explanatory principle of more general value. If this social devaluation is assimilated by the individual, as commonly occurs, he will himself introduce a negative force into many of the situations in which he finds himself. His self evaluation also will influence his choice of situations.

In the case of children who are disabled, the self-evaluation concept emphasizes the important role of parents. By accepting and respecting the child as he is, they can engender a feeling of self regard that will provide an effective defense against the depreciating attitudes he is certain to encounter in many social situations.

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HOWARD FREIBERGER (*Research and Development Division, Prosthetic and Sensory Aids Service, Veterans Administration, New York, N. Y.*): During the past one and a half years I have devoted my time to work with sensory aids, chiefly for the blind. I have found that the difficult problems of sensory replacement almost never yielded to the efforts of workers in one discipline or, for that matter, to the combined efforts of men from several disciplines, who, as individuals, think unilaterally only within their own spheres. At some time in the development of any research project, preferably at the very

inception and certainly at all times thereafter, there must be a "meeting of the minds." The physical and engineering scientist must be willing to adopt some of the philosophies and techniques of the biologist and psychologist, and vice versa. This is not, in this day of a vastly complex and gigantic fund of human knowledge, to relieve the individual from being a specialist in his field, but only to suggest that he must have some understanding of the capabilities and limitations, not only of his cooperating fellow workers, but also of their several chosen disciplines.

Many electrical and mechanical aids for the blind in the field of reading machines and guidance devices have been designed and built, yet very few, if any, have achieved the success that comes only when a significant number of the disabled find them satisfactory enough to use. It is quite logical that such instruments are designed and built chiefly by engineers. The unfortunate thing is that they often performed only for their builders and never for a significant number of the disabled. I think the reason for this is, in part, the lack of sufficient interdisciplinary exchange that has characterized earlier work in this field. There is every reason to believe, however, as demonstrated by the very publication of this monograph and by increased emphasis on such relatively new disciplines as human engineering and information theory, that the need for interdisciplinary activities in sensory-aids research is gaining widespread recognition.

Perhaps I shall now list briefly some of the research projects we are currently supporting in the field of visual sensory aids: A guidance device for the blind is being developed at Haverford College, Haverford, Pa., with physicists, electrical and electronic engineers, and blind subjects participating. The Spelled-Speech Project of research for automatic readers usable by the blind is being conducted by a psychologist at the University of Southern California, Los Angeles, Calif. A project, Research on Audible Outputs of Reading Machines for the Blind, at the Haskins Laboratories, Inc., New York, N. Y., utilizes the abilities of engineers, linguists, psychologists, and speech specialists. A second project at the same laboratories, Output Characteristics and Construction of an Interim Word Reading Machine, draws on an equally varied set of talents. The Development and Evaluation of Aural Reading Devices for the Blind, at the Battelle Memorial Institute, Columbus, Ohio, uses the services of engineers, linguists, psychologists, and blind subjects. The development and evaluation of a personal-type reading machine for the blind, at H. A. Mauch Research and Development Laboratories, Dayton, Ohio, takes ideas from electronic, acoustic, linguistic, and psychological fields. In my own laboratory I am trying to perfect a visagraph-type instrument that will emboss a tactual impression in aluminum foil of ink print material, and also a Braille-producing code translator to accept teletypesetter tape and produce Grade I Braille. Even though I am classified by the federal government as an electronic scientist, I can assure you that, in the pursuit of these problems, my efforts have spanned many and diverse disciplines.

J. E. HAWKINS, JR. (*Department of Otolaryngology, New York University-Bellevue Medical Center, New York, N. Y.*): My only qualification as an inter-

disciplinarian is that I am a neurophysiologist member of a clinical department of otolaryngology. This is not an unusual affiliation in the field of hearing, where the interdisciplinary approach has long been the rule. That this approach has sometimes proved valid is attested by the remarkable contributions to our knowledge of the ear made by the physicists H. von Helmholtz, H. Fletcher, and G. von Békésy.

The first efforts of the otolaryngologist toward the rehabilitation of the deaf consisted in teaching them to read lips. Later came electronic hearing aids and, with them, special instruction in speech for severely deafened children. Recently the surgeons have been taking matters into their own highly trained hands. J. Lempert has perfected the fenestration operation, and S. Rosen the stapes mobilization, both for the restoration of useful hearing in ears deafened by otosclerosis. F. Zöllner has introduced tympanoplasty for the repair of conductive defects in the middle ear caused by chronic infection. Apart from the surgical skill required for these operations, other necessary conditions have been met by contributions from other disciplines: the operating microscope, the means of illumination of the dark recesses of the middle ear, and a wide choice of antibiotics for the control of infection. These operations already have restored useful hearing to hundreds of patients with conductive hearing loss.

Although much is being done for patients with conductive loss, almost everything remains to be done for those with perceptive loss. Obviously we shall always need to be able to recognize deafness in children at as early an age as possible, so that they can receive auditory and speech training when it has the greatest chance of success. We could use further improvements in hearing aids, since miniaturization is not the only worthwhile goal. Binaural aids will be helpful to many patients, both for localization of sound and for the suppression of unwanted noise, which seems to be much less disturbing when heard with both ears. Also, we should re-examine the possibilities of specially tailored hearing aids for those nerve-deaf patients who cannot tolerate ordinary instruments. Such a patient might be happier with the frequency characteristic of his hearing aid adjusted to his loudness contour at a comfortable listening level, with adequate limiting to prevent overstimulation by transient noises.

Although mechanical prostheses for the middle ear have never found general favor, the prosthesis designed by M. Aubert of Montpellier, France for sealing perforations in the ear drum seems to have considerable merit. The most ambitious experiment with an electric prosthesis has been performed recently by A. Djournio and B. Vallencien of Paris, France. These investigators fastened a tiny induction coil to the temporal muscle of a totally deaf patient and implanted electrodes so as to stimulate a branch of the eighth nerve when the patient was in the field produced by a suitably large primary coil. When a microphone and amplifier were included in the primary circuit, he was able to "hear" speech. Although it remained largely unintelligible, with practice he came to recognize a few words.

The limitations of such a device are easily seen. It is applicable only in cases where the auditory nerve is intact, and it cannot possibly replace the analyzing and encoding functions of the cochlea. Nevertheless, the experi-

ment cannot be dismissed lightly. Its success is best judged by the reported reactions of the patient who, with continued use of the device, came to feel that he was in contact with his surroundings, so long as the primary coil was connected to the microphone and he was in the field. When the circuit was broken, he felt completely isolated. Unfortunately, the possibility of doing anything similar for patients with severe perceptive deafness by direct electric stimulation of the auditory area of the cerebral cortex seems extremely remote.

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